Welded Repair and Maintenance in the Space Environment

by

Vasilios Nikou

B.S. Naval Engineering, Hellenic Naval Academy, 1994

Submitted to the Departments of Ocean Engineering and Material Science and Engineering
in Partial Fulfillment of the Requirements for the Degrees of

Engineer Degree in Naval Engineering
and
Master of Science in Materials Science and Engineering

at the
Massachusetts Institute of Technology
June 2003

Author. ....
Department of Ocean Engineering
May 9, 2002

Certified by ....
Koichi Masubuchi
Professor of Ocean Engineering and Materials Science Emeritus
Thesis Supervisor

Certified by ....
Patricio F. Mendez
Research Affiliate
Thesis Supervisor

Certified by ....
Thomas W. Eagar
Professor of Materials Science and Engineering
Thesis Supervisor

Accepted by ....
Michael Triantafyllou
Professor of Ocean Engineering
Chairman, Departmental Committee on Graduate Studies

Accepted by ....
Harry L. Tuller
Professor of Materials Science and Engineering
Chairman, Departmental Committee on Graduate Studies

Welded Repair and Maintenance in the Space Environment

by

Vasilios Nikou

Submitted to the Departments of Ocean Engineering and

Materials Science and Engineering

on May 9, 2003, in partial fulfillment of the

requirements for the degrees of

Engineer's Degree in Naval Engineering

and

Master of Science in Materials Science and Engineering

Abstract

The feasibility of using earth bounded welding techniques in the space environment has been investigated. A literature survey on welding in space reveals numerous aspects about the work done in different countries. The survey indicates the need of a more detailed focus, since no welding experiments have been performed in space since July 1984 (Salyut-7). Addressing the peculiarities of different welding processes, such as environmental restrictions, helped in evaluating and analyzing the selected processes. In order to study the use of a welding process, one should also analyze the ways to test the welds produced. Consequently, non-destructive testing (NDT) techniques with potential use in the space environment were evaluated. A comparison of the various NDT techniques showed parameters, which had not been previously considered, for instance materials to be welded and type of welding processes to be used. The most probable candidates for use in the space environment were ultrasonic, radiographic and eddy current techniques. Even though mathematical modeling is not the main part of the thesis, an existing model was used in order to examine the impact of gravity on defect formation, and humping in particular, in the welding pool. Different results were generated for the Earth environment as well as the simulated space environment inside a spacecraft.

Thesis Supervisor: Koichi Masubuchi
Title: Professor of Ocean Engineering and Materials Science Emeritus

Thesis Supervisor: Patricio F. Mendez, Ph.D.
Title: Research Affiliate

Thesis Reader: Thomas W. Eagar
Title: Professor of Materials Science and Engineering

Acknowledgements

I would like to thank the people who worked with me on this thesis. Without their guidance and support, the completion of this project would have been impossible. First, I would like to thank Professor Koichi Masubuchi, who was the first person that proposed I consider a thesis on welding in space. Ever since I met Professor Masubuchi, I feel that I gained from his wisdom and his knowledge on welding. I would also like to thank Professor Thomas W. Eagar for helping me identify the problems that the research should address. Every single one of our meetings was a unique experience for me.

Dr. Patricio Mendez was the person that spent most of the time with me on the research of this thesis. I would like to specifically thank him for devoting his time and making me feel more like his friend than his advisee. I would also like to thank Jerilyn Hill who helped me considerably regarding all the administrative issues. Finally, special thanks to Toby Bashaw for letting me use his equipment and teaching me how to weld, as well as showing to me some of the welding "tips" that could not be found in books.

Contents

List of Figures

List of Tables

List of Abbreviations

AE	Acoustic Emission
AIAA	American Institute of Aeronautics and Astronautics
ASRM	Advanced Solid Rocket Motor
B	Brazing
CASI	Center for AeroSpace Information
CSA	Canadian Space Agency
DB	Dip Brazing
EBW	Electron Beam Welding
ESA	European Space Agency
EVA	Extra Vehicular Activity
FB	Furnace Brazing
FSW	Friction Stir Welding
FW	Friction Welding
GHTAW	Gas Hollow Tungsten Arc Welding
GMAW	Gas Metal Arc Welding
GTAW	Gas Tungsten Arc Welding
HAZ	Heat Affected Zone
IB	Induction Brazing
INPE	Brazilian Space Agency (Instituto Nacional de Pesquisas Espaciais)
IRB	Infrared Brazing
ISI	Institute of Scientific Information
ISS	International Space Station
ISWE	International Space Welding Experiment
IVA	Intra Vehicular Activity
LASER	Light Amplification by Stimulated Emission of Radiation
LBW	Laser Beam Welding
LEO	Low Earth Orbit
MMC	Metal Matrix Composites
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency of Japan
NDT	Non-Destructive Testing
PAW	Polarity Arc Welding
RKA	Russian Space Agency
RPW	Resistance Projection Welding
RSEW	Resistance Seam Tracking Welding
RSW	Resistance Spot Welding
RW	Resistance Welding
TB	Torch Brazing
TWI	The Welding Institute
UHT	Universal Hand Tool
VPPAW	Variable Polarity Plasma Arc Welding
VUV	Vacuum Ultraviolet Radiation

1. Introduction

Several countries support the program of the International Space Station (ISS). Currently there are 16 countries working together to construct the ISS. The agencies involved are: National Aeronautics and Space Administration (NASA), the Russian Space Agency (RKA), the European Space Agency (ESA), the National Space Development Agency of Japan (NASDA), the Canadian Space Agency (CSA) and finally the Brazilian Space Agency (INPE-Instituto Nacional de Pesquisas Espaciais).
The first step was on January 29, 1998, when 15 countries met in Washington DC to agree to an unprecedented collaboration as partners in the design, development, operation and use of an international space station. The program officially started on November 1998 with the launch of 'Zarya Control Module'. Today, five years later, the International Space Station (ISS) is the largest, most expensive laboratory ever built in space. The station and its crew draw from the resources and scientific knowledge of multiple countries to perform state-of-the art research in the space environment. Four Expedition crews have occupied the station for up to six months at a time, and the Expedition 5 crew is currently living and working in space. The ISS is scheduled for core completion by the year 2004, with continued assembly through 2006.

In the ISS project, mechanical joints will erect all the Station. Welding is not considered for the assembly. Whereas, the advantages of welding as a joining process over the mechanical joints (i.e. lighter weight and higher reliability) are well known, which is why welding is one of the most advanced, practical, and safe fabricating processes on earth. It is only a matter of time before welding will be used for fabrication in space as mankind evolves to its destiny in the habitation of extra-terrestrial places.

While welding used for fabrication is still a vision for the near future the use of welding for repair and maintenance in the space environment is already a necessity for all kinds of structures launched in space by man. As the operational lifetime of space systems is increased, the incidence of system degradation and malfunction becomes more common. Systems like piping and fluid lines have high operating pressures (up to 6000 psi) and a malfunction may lead to a disastrous outcome if not repaired on time. Damage to space structures can result also from accidental misuse of the equipment. In a few words, failures of critical spacecraft systems do occur despite the best efforts of the design engineers. In addition to this, one common cause of damage is “space debris”, or miscellaneous small and large pieces of disintegrated satellites, materials jettisoned from spacecrafts and other space materials. This debris is traveling at high speed and a resulting collision, even with a small piece of material, can cause significant damage.

The on-orbit repair of the space-assets has proven to be more economical than to return them to earth. The Soviet space program has already used welding to repair Soyuz space station tubing. Bearing all the above in mind one can conclude that for every structure launched in the space, we need to be prepared for its maintenance and repair. Both the United States and the former Soviet Union have carried out welding experiments in space. The United States used Skylab to weld 2219-T87 aluminum alloy, 304 stainless steel, and pure tantalum samples. The Soviet program used Soyuz to perform its experiments. Both of these efforts involved electron-beam welding.

The purpose of this thesis is to assess the feasibility of using welding in space. A literature survey on space welding was performed beginning from 1983 up to date and a brief analysis of the concentration of the publications is given. A similar study was performed by professor Koichi Masubuchi, A. Imakita and M. Miyake in a paper published in the Welding Journal in April 1988 [1]. Furthermore, a basic description of the welding processes that appear to have the best potential for space application is given.

The uniqueness of the space environment is analyzed and the most important factors of that environment (micro gravity, high vacuum and extreme temperature differences) are discussed. An analysis table of some of the welding processes gives a better understanding of the various considerations, limitations and problems of each technique as far as welding in space is concerned.

Emphasis is also given in a field that has not received much attention, but jumped to prominence with the space shuttle Columbia tragedy: the possible inspection techniques (non destructive testing – NDT) that might be used for welding evaluation in space. Another analysis of the possible NDT methods and the obstacles for using them in the space environment favors some NDT techniques over others.

As far as welding research on earth is concerned, it was often relied on a “trial and error” approach, which in space is too expensive and often impractical. Thus, welding research in space probably needs to be approached differently. A research, based mainly on experiments in virtual environment and mathematical models should be more fruitful in this case. An example of such a model is used in the last part of the thesis. The model is used to predict the onset of defects in the weld pool in the space environment. The equations for this part of the thesis are valid only for the gas tungsten arc welding process.

2. Background of Welding in Space

2.1 Literature Survey on Welding in Space

A literature review on welding in the space environment and related technologies was performed as part of this thesis. The literature survey concerns a range of publications beginning from 1983 up to date and a brief analysis of the concentration of the publications is given. This study is an update of a survey of welding in space by, A. Imakita et.al. [1].

The results of the literature review are presented in Appendix A, involving the title, year, author, and place of each publication. In Table 1 we could see the number of publications per country, over the last 20 years. The same data is graphically presented in Figure 1.

The survey indicates that the USA is by far the country where most work has been done in the area of welding space. The data collected in the survey may be misleading in a way, as most databases available for the survey were the ones used by the Massachusetts Institute of Technology, which favor the US publications. Databases from other countries such as Japan, or even Europe, were not easy to access.

The only country that has done welding experiments in the space environment is Ukraine, a member of the former Soviet Union. The processes that were tested are gas metal arc welding, plasma arc welding, and electron beam welding. All of these were tested in the Soyuz-6 space flight. In each case, they demonstrated the viability of arc welding in space, but felt that better control was available through the electron beam route [2]. The Paton Welding Institute is the country's main welding research center for welding in space technologies. In the Ukraine, a lot of research was conducted in the EBW process and an electron beam gun was constructed for this purpose. The Ukrainians, together with the Russians, were planning on conducting space welding experiments on MIR but they were not able to complete them before MIR was abandoned.

In the USA, results from welding in space research were not up to expectations and NASA decided to commence collaboration with the Ukraine. In November 1994, NASA and the Paton Welding Institute in Kiev, Ukraine, initiated a joint project called the International Space Welding Experiment (ISWE) to be performed in 1997. This project involved the flight demonstration of the Ukrainian Universal Hand Tool (UHT), an electron beam-welding tool developed by Paton, to assess the capability to perform new emergency repairs on the International Space Station. The UHT is an electron beam tool that does not produce dangerous X-rays and so frees mission planners from the need to protect astronauts from their effects. The device has been tested by Soviet cosmonauts during space walks in 1984 (Salyut 7). The processes that were going to be tested in space were EBW and brazing. Even though most of the necessary preliminary trials and training were under way, the ISWE program was aborted. There have not been any other welding experiments conducted in space since those done on the Salyut 7. The International Space Welding Experiment was removed from the International Space Station (ISS) experiments. Not much more has been done the next few years, but currently NASA has an ambitious ongoing project that considers EBW as the best process to be used not only for repair and for maintenance in space but also for fabrication of large space structures.

Japanese researchers have been working mainly on arc welding and brazing for the space environment. They invented a new method of GTAW, named Gas Hollow Tungsten Arc Welding (GHTAW), in order to be able to weld using arc in vacuum. This method is better described in paragraph 3.1.3 Gas Hollow Tungsten Arc Welding (GHTAW).

Countries	Number of Publications	Percentage
Canada	3	1.15%
China	2	0.77%
Finland	1	0.38%
France	3	1.15%
Germany	8	3.08%
India	4	1.54%
Italy	4	1.54%
Japan	37	14.23%
Russia	4	1.54%
UK	3	1.15%
Ukraine	23	8.85%
USA	168	64.62%
Total	**260**	**100.00%**

Table 1: Number of publications on welding in space per country.

Year	Number of Publications	Percentage
1983	8	3.08%
1984	4	1.54%
1985	12	4.62%
1986	14	5.38%
1987	9	3.46%
1988	10	3.85%
1989	16	6.15%
1990	16	6.15%
1991	26	10.00%
1992	18	6.92%
1993	21	8.08%
1994	14	5.38%
1995	10	3.85%
1996	16	6.15%
1997	13	5.00%
1998	19	7.31%
1999	14	5.38%
2000	12	4.62%
2001	8	3.08%
Total	260	100.00%

Table 2: Total number of publications on welding in space per year

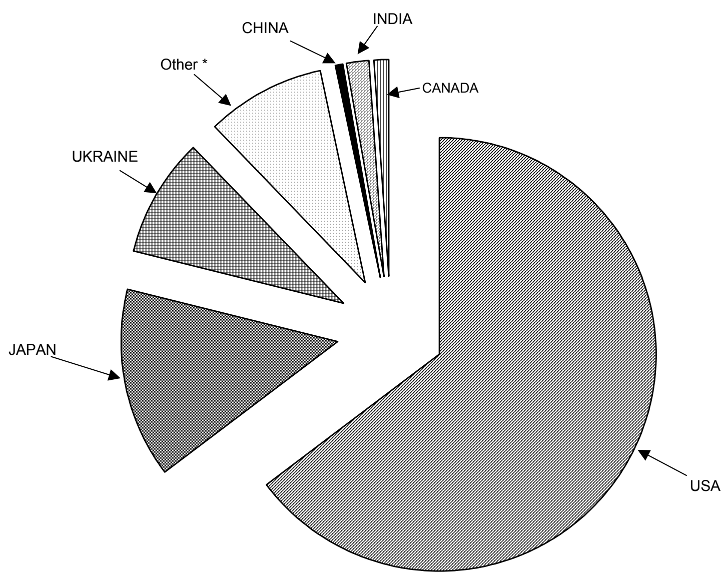


Figure 1: Graphical representation of publications on welding in space per country.

* All the other countries (Finland, France, Germany, UK, Russia) shown in the pie graph in Figure 1 have minor contribution in welding in space.

Finally, in Table 3 there is a summary of the keywords found in the publication survey. The vast majority of the publications were found through various databases provided at MIT. All these databases are listed in Table 4. A summary of all the articles found during this research (title, author(s), year of publication, and country of publication) could be found in Appendix A.

Keyword	Repetirions	Keyword	Repetirions
Arc Welding	9	EVA	52
EB Welding	24	Fabrication	4
Friction Welding	4	Inspection	11
Fusion Welding	13	ISWE	6
GHTA	19	Maintenance	2
GTAW	13	Materials	17
Laser Welding	11	Plasma Arc Welding	15
Stud Welding	9	Plasma Keyhole Welding	2
VPPAW	7	Repair	5
Aluminum	78	Robotics	16
Automation	16	Stainless Steel	44
Environment	6	Temperature	33

Table 3: Survey keywords analysis for publications on welding in space

As we see in the keyword analysis in Table 3, the welding processes that were mainly discussed in the publications since 1983 involve: electron beam, friction, gas hollow tungsten, gas tungsten arc, laser, plasma, and variable polarity plasma arc welding. Out of these processes, electron beam welding was mentioned the most followed by gas hollow tungsten arc welding and gas tungsten arc welding.

A lot of emphasis has been given in the area of materials, with aluminum and steel dominating the references. Another interesting point is that there are only a few publications for either repair or fabrication in the space environment. The later was more or less expected since little work has been done in welding in space during the past twenty years, and people still believe that the best way to erect space structures is by mechanical joints. The cancellation of the international space welding experiment (ISWE) as well as the fact that there has not been a single welding experiment in space since the Salyut 7 (July, 1984) point out that more research needs to be done in the area of welding in space.

1	**NASA Database (CASI) Technical Reports Server** National Aeronautics and Space Administration
2	**Web of Science** ISI
3	**Aerospace and High Technology Database** Cambridge Scientific Abstracts
4	**AIAA Technical Meeting Papers** American Institute of Aeronautics and Astronautics
5	**WELDASEARCH** Cambridge Scientific Abstracts

Table 4: Databases used for literature survey.

2.2 Considerations

The literature survey and the brief keyword analysis give us an overview of what has been written in the past about welding in space. It also raises the following interesting points.

2.2.1 Welding Shop Location

There is only one paper found that mentions the need of a special place to be used in the space station(s) for welding repair or fabrication. In some cases, especially in repairs, it might be inevitable to weld anywhere else than on site. In all other cases, the use of a place especially designed for welding is a necessity. Up to now, welding was done either in the open space (EVA), or in the living quarters (IVA). Not only the space in the living quarters is very limited, but also that is where all the crucial equipment is furnished. Thus, the safety requirements are very strict and prohibit the use of any welding process. There should be a place, such as the cargo bay, (something in between the living quarters and the open space environment) that could be used to weld, whenever the workpiece(s) can be moved. Such a place could be also used as an all-purpose machine/repair shop.

2.2.2 Automation

In order to establish a permanent human presence in space we must develop technologies to repair and construct the various space structures that are reliable, cost efficient and most importantly time efficient. The experiments that concern welding in space and were conducted in the past were done manually. This should not be the case for the most extensive use of welding in space. For EVA repairs, the astronauts are highly restricted by the space suit, which makes welding accurately almost impossible. As far as fabrication is concerned, automation is very attractive, for productivity reasons. In space, time “costs” much more compared to earth. One of the ways to reduce welding time, when used in a large scale, is automation.

3. Welding Processes for Application in Space:

In principle, the space environment enables all currently available methods of joining materials in industry to be used; mechanical (threaded, hinged, lock, rivet, etc.), adhesion (bonding, brazing, coating), and welding. Each of these methods has its advantages and disadvantages [3] .

Over the life time of the structures in space some kind of damage is bound to occur on the structure due to human factors or accidents, degradation and wear of critical or expensive hardware, or damage of outer shell from space debris and micrometeorites. In many of these cases, welding provides the best if not the only means of making high quality, economical repairs in timely fashion.

Welding has inherent advantages over mechanical joints for the following reasons:

1. Welded joints weigh less than mechanical joints (thus the structures have reduced mass-to-orbit).
2. Air tightness can best be achieved with welded joints.
3. Mechanical joints may become loose over the service life of the structure (experience has shown that mechanical couplings for fluid lines on spacecraft do not provide required reliability [4])
4. Welded structures have high rigidity
5. Welded joints have higher strength over a wide temperature range compared to mechanical joints.

Today there are many welding processes, but of the many that exist only a limited number has been seriously studied for use in space. Most of these processes have not been tested under actual space conditions but under conditions simulating space, such as in vacuum chambers, in parabolic flights, or both.

At this point, a classification of the welding processes considered for use in space is given, followed by a brief description of each welding process.

a) <u>Fusion Welding:</u> in this type of welding, the areas to be welded are heated until they melt together. The welding processes involved in this type of welding are arc welding, laser welding and electron-beam welding.

b) <u>Solid-phase welding:</u> in this type of welding, the parent metals do not melt. Pressure is applied and mechanical deformation is dominant. The processes involved are friction welding and friction stir welding.

c) <u>Electrical Resistance Welding:</u> in this type of welding, the parent metal is first heated by passage of electric current and then pressure is applied. The process involved is resistance spot welding.

d) <u>Liquid-solid welding:</u> in this type of welding, the parent metals are heated lower than the melting point and molten metal is added to form solid joining. The process involved is brazing.

3.1 Arc Welding

Arc welding accounts for the largest volume of welding performed today. The most important processes are Gas Metal Arc Welding (GMAW), Gas Tungsten Arc Welding (GTAW), and Plasma Arc Welding (PAW).

3.1.1 Gas Metal Arc Welding (GMAW)

Gas Metal Arc Welding is a gas shielded-arc welding process in which the weld is created by an electric arc formed between the consumable electrode and the work piece. The electrode is in the form of a filler wire that is mechanically driven into the weld zone. The shielding gas is usually argon or helium (both inert gases). The metal is transferred to the work piece in globular drops or a spray of fine droplets, depending on welding current, electrode material, and diameter, shielding gas and gravity.

Experiments using GMAW in space were done by the former Soviet Union on Soyuz-6. Some results of the experiment include [5]:

- At low current, molten drops grew large and remained attached to the electrode for a long period.
- Increasing the current increased the electromagnetic effects.
- Stable metal transfer was achieved when using the short circuit technique.

- Weld beads bulged slightly in the center due to surface tension, resulting in the decreased weld penetration.
- When welding in a vacuum, it was possible to achieve a stable arc in the vapor of the electrode material.

GMAW is one of the most popular welding processes in the world because of its flexibility and low cost. The drawback for its use is that the large size of the heat source (compared with processes such as EBW, LBW and PAW) causes the welds to have inferior mechanical properties than other processes. This process was the main welding process used for the construction of the fuel and oxidizer tanks for the Saturn V rocket (2219 aluminum alloy for the first stage). One of the current applications of GMAW is in the automatic welding of the vanes of the Patriot missile [6].

3.1.2 Gas Tungsten Arc Welding (GTAW)

Gas Tungsten Arc Welding is similar to GMAW in its use of an inert shielding gas but the tungsten electrode is not consumed. Shielding gas is fed through the torch to protect the electrode, molten weld pool, and solidifying weld metal from contamination by the atmosphere. The electric arc is produced by the passage of current through the conductive, ionized shielding gas. The arc is established between the tip of the electrode and the work piece. Heat generated by the arc melts the base metal. A GTAW torch holds the tungsten electrode, which conducts welding current to the arc, and provides a means of conveying shielding gas to the arc zone (Figure 2). If filler material is required, a welding rod can be fed into the weld zone and melted. GTAW can generate a more intense heat source than GMAW; therefore, producing welds with less distortion at a similar cost. For applications where dimensional tolerances and residual stresses must be strictly controlled, this process is not as good as other welding methods such as electron beam welding, laser beam welding or plasma arc welding. GTAW was used together with GMAW to weld the 2014 and 2219 aluminum alloy in the fuel and oxidizer tanks in the Saturn V rocket, as well as for the Titan IV launch vehicle [6].

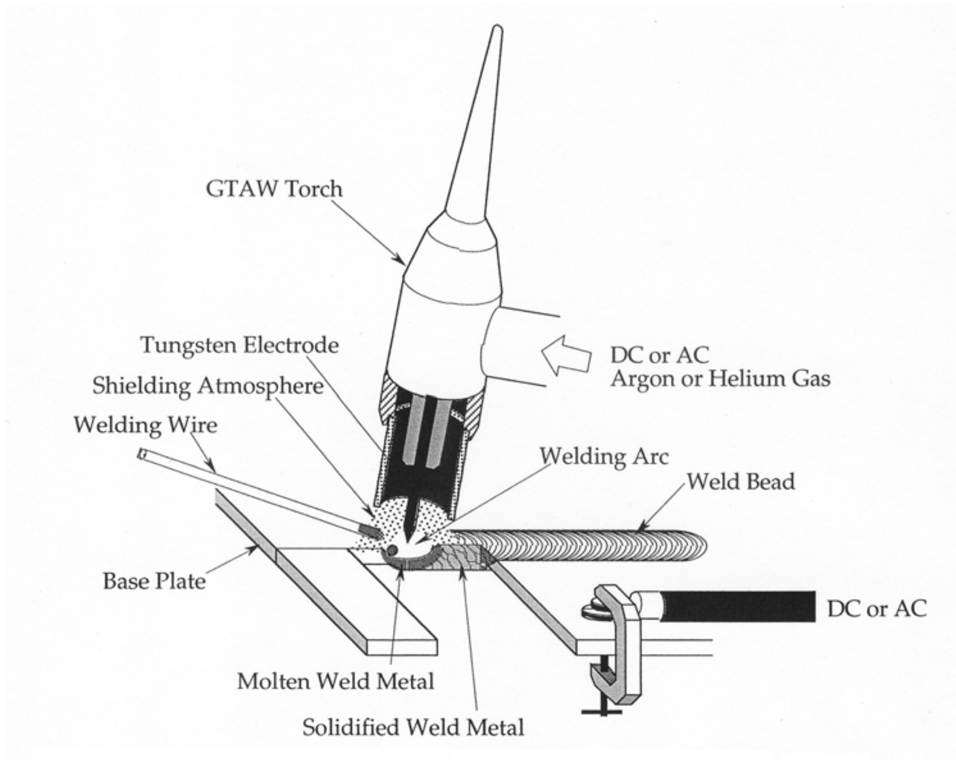


Figure 2: Gas Tungsten Arc Welding operation torch assembly. [7]

3.1.3 Gas Hollow Tungsten Arc Welding (GHTAW)

Gas hollow tungsten arc welding is a variation of GTAW, using a hollow tungsten electrode to overcome the problems of welding in vacuum. In welding experiments, the vacuum in a chamber causes the inert gas to diffuse from the nozzle; therefore, it is necessary to keep the gas flow running around the tip of the electrode to strike the arc within an inert environment. This is done using a hollow electrode.

3.1.4 Plasma Arc Welding (PAW)

Plasma Arc Welding is also one of the arc welding processes. In this process, the plasma is produced inside the torch instead of between the torch and the workpiece. This produces more concentrated and more controllable arcs. The principle of plasma arc welding can be seen in Figure 3. The plasma is a hot ionized conducting gas that is turned into a jet when sent through a nozzle. Advantages of the constricted arc nozzles over the gas shielded-arcs include flame stability and more concentrated power, making the plasma jet very effective at high-speed cutting. Plasma arcs have been used for cutting, coating, and welding.

This process is also used for the welding of the Advanced Solid Rocket Motor (ASRM) of the Space Shuttle. The ASRM is made of HP-9-4-30 steel by Lockheed Martin [6].

Experiments using PAW were also done by the former Soviet Union on Soyuz-6. Some results of the experiment include [8]:

- Arc ignition, arc stability, and focus of anode spot were affected by the amount of vacuum.
- On thin samples, weld formation was similar to those done on earth, but in space surface tension forces dominated the formation.
- Sound welded joints were obtained.
- Some porosity was found along the fusion line in the titanium alloy.
- Arc constriction was difficult when the chamber was vented into space.

3.1.5 Variable-polarity Plasma Arc Welding (PAW)

One of the latest variations of plasma arc welding is variable-polarity plasma arc welding (VPPAW) commercialized by Hobart Brothers. This variation was developed by the aerospace industry for welding thick sections of alloy aluminum, specifically for the external fuel tank of the space shuttle [9]. In this process, the melting is in the keyhole mode. The negative part of the cycle provides cathodic cleaning of the aluminum work piece, while the positive portion provides the desired penetration and molten metal flow. Tests showed that the best duty cycle for this process involves a negative current of 15-20 ms and a positive one of 2-5 ms, with a positive current of 30-80 A higher than the negative current [10]. The concentrated heat of VPPA causes significantly less angular distortion than GTAW, as shown in Figure 4, where there is a comparison of angular distortion of PAW (top) and GTAW (bottom). The more concentrated heat source in PAW causes significantly less distortion than GTAW [6].

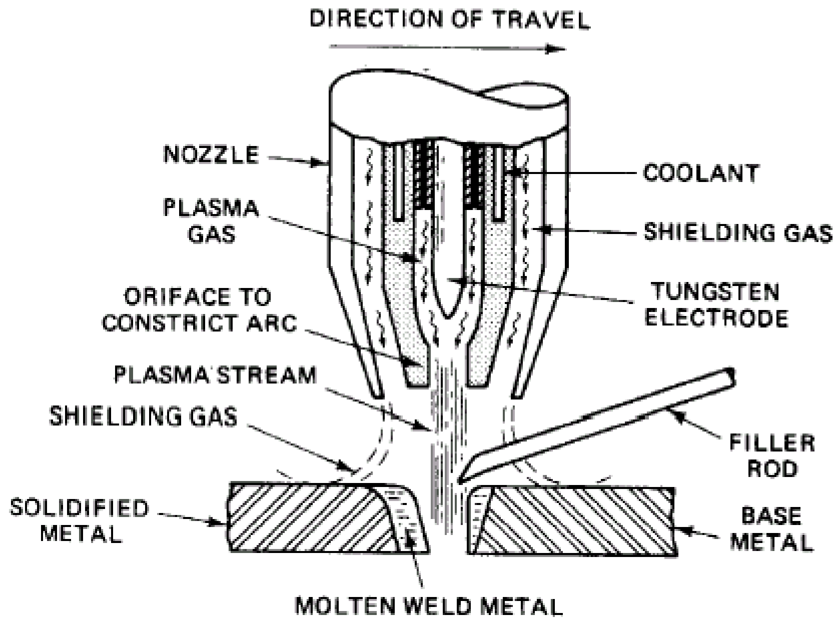


Figure 3: Principle of Plasma Arc Welding [9]

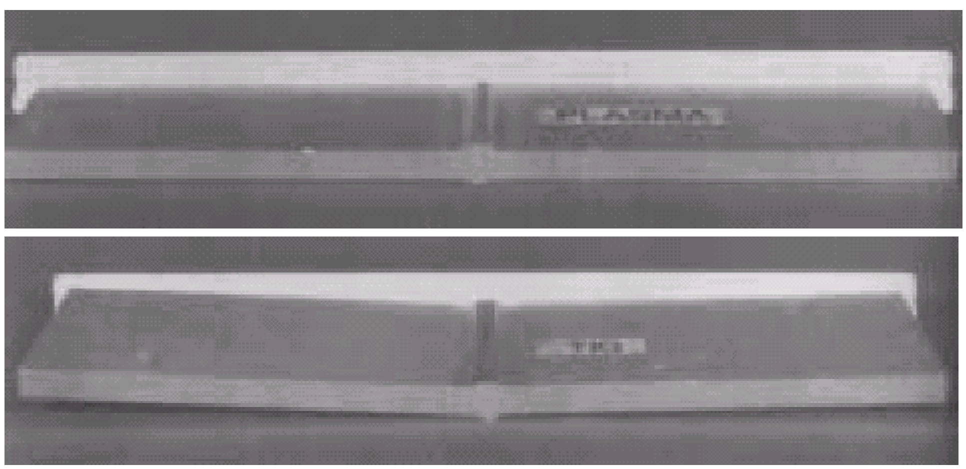


Figure 4: Comparison of angular distortion of plasma arc welding and GTA welding [6]

3.2 Laser Beam Welding (LBW)

The word laser is an acronym; it stands for Light Amplification by Stimulated Emission of Radiation and refers to the way in which the light is generated. Maiman, an American scientist, discovered laser light for the first time in the late 1950's. He found that a crystal of ruby generates a special kind of light when an internal energy transition occurs within its molecule. Unlike other lights, laser light has unique features such as a single wavelength and an electromagnetic coherency. Those features give a focused laser beam an extremely high energy density that can be applied in material processing including cutting, drilling, and welding. Since Maiman's historic discovery, a number of materials that can generate the laser light have been studied. As a result, today, a couple of laser sources, CO_2 gas and YAG crystal, is commercially and widely used for industrial applications.

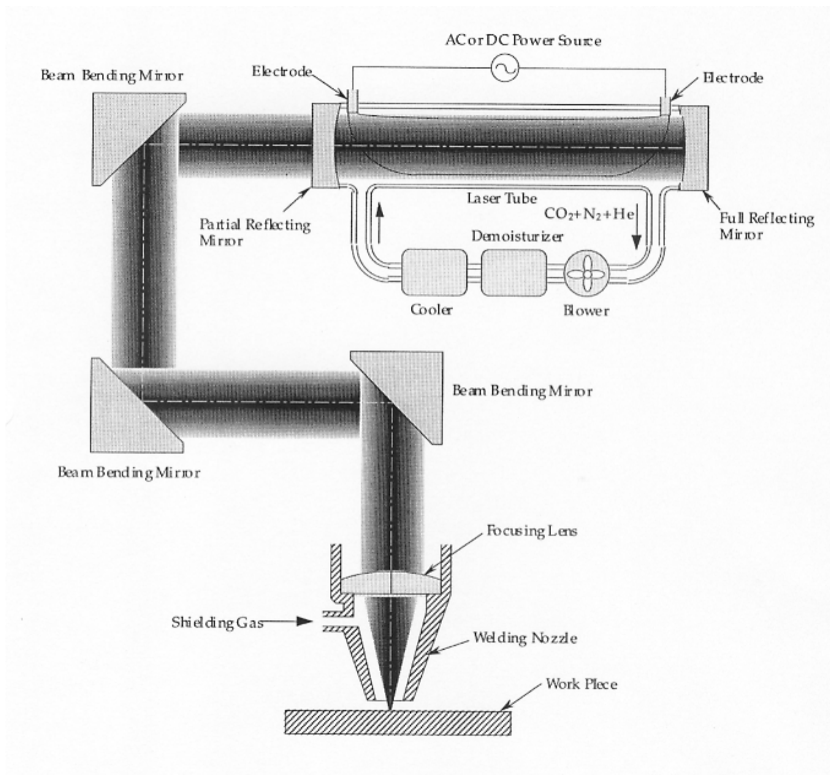


Figure 5: Schematic illustration of CO2 laser resonator and processing equipment [7]

Figure 5 shows a schematic illustration of an axial flow type CO_2 laser resonator and processing equipment [7]. A CO_2 laser resonator has a glass tube, which contains CO_2 and other auxiliary gases, a couple of mirrors and electrodes for a glow discharge. To promote the energy transition in the CO_2 molecule, the gas is first energized by using a glow discharge. Immediately after being energized, CO_2 molecules lose their internal energy by an internal energy transition and generate laser light of 10.6μm wavelength.

Laser light generated by a CO_2 molecule stimulates other molecules to create the laser beam. In this manner, laser light is amplified in the tube to a certain strength that is determined by the volume of the tube and the energizing efficiency by glow discharge.

Laser beam welding; together with electron beam welding, can deliver the most concentrated heat sources for welding, with the advantages of higher accuracy as well as smaller distortions. In laser beam, however, the efficiency of the energy transfer from the laser beam to the work piece is usually not as high as that of electron beam welding, because of the reflective nature of molten metals.

3.3 Electron Beam Welding (EBW)

In electron beam welding, the work piece is bombarded with a highly focused beam of high velocity electrons. The energy of these electrons is converted to heat upon impact. The electron beam used is generated by an electron gun in a fully automatic process. Welding is performed in vacuum to prevent the scattering of electrons due to collisions of gas molecules and thus to allow uninterrupted electron travel.

In Figure 6 we see a cross section of a typical electron gun. Electrons are extracted from a heated filament and accelerated by a high voltage between the filament and the anode. The accelerating voltage is usually up to 150 KV. An illustration of the EBW process can be seen in Figure 7. When the electron beam is highly focused at the work surface, the energy density in the heated area could become 100,000 times that of the tungsten arc.

The high intensity of the electron beam generates welds with a small heat affected zone (HAZ) and little distortion as shown in Figure 7. The cross section of the weld performed with EBW is shown on the left and the one performed with GTAW on the right. The higher heat intensity of the electron beam creates a much smaller fusion zone and HAZ [11]. This process presents an advantage over laser beam welding in that it has no problems with beam reflection on the molten metal; however as we mentioned before it needs to operate in vacuum. The later makes this process especially suitable for welding of titanium alloys that cannot be welded in an open atmosphere, for space applications, where vacuum is unavoidable.

Electron beams are easily distorted by magnetic fields. In some cases, thermoelectric currents are produced during electron beam welding of dissimilar materials. If the materials are very thick, the currents will produce magnetic fields, which will distort the beam causing it to deviate from the weld seam. Lasers on the other hand are not affected by stray magnetic fields.

Critical titanium structural components are being EB welded for the Eurofighter (attachment of the wings and fin to the fuselage) and Boeing's F-22 (aft fuselage). A remarkable application of EBW is in the construction of the oxygen and fuel tanks of the Russian Energia rocket Figure 10. Due to the large size of the tanks, the vacuum is created locally, and sealed with ferro-electric liquids [6].

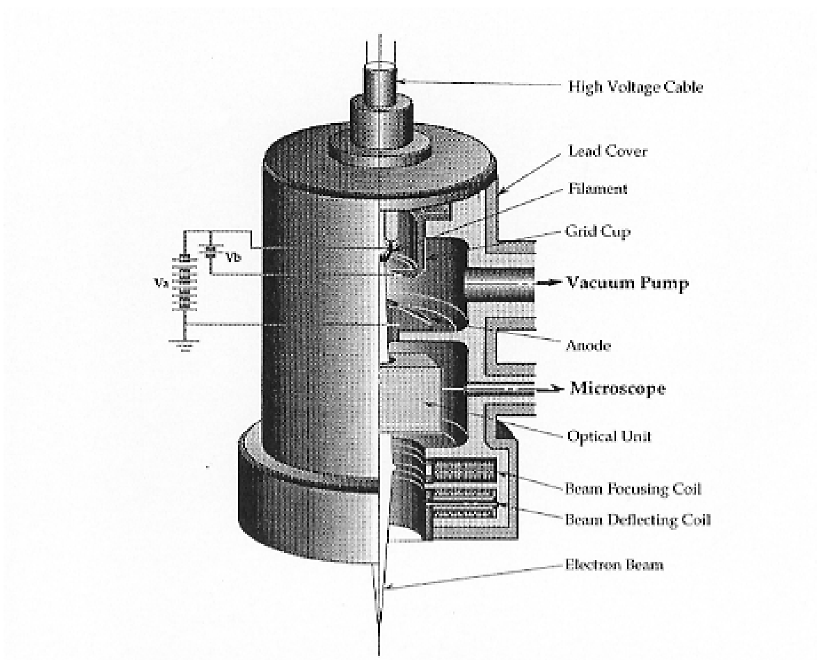


Figure 6: Cross section of typical electron gun [7]

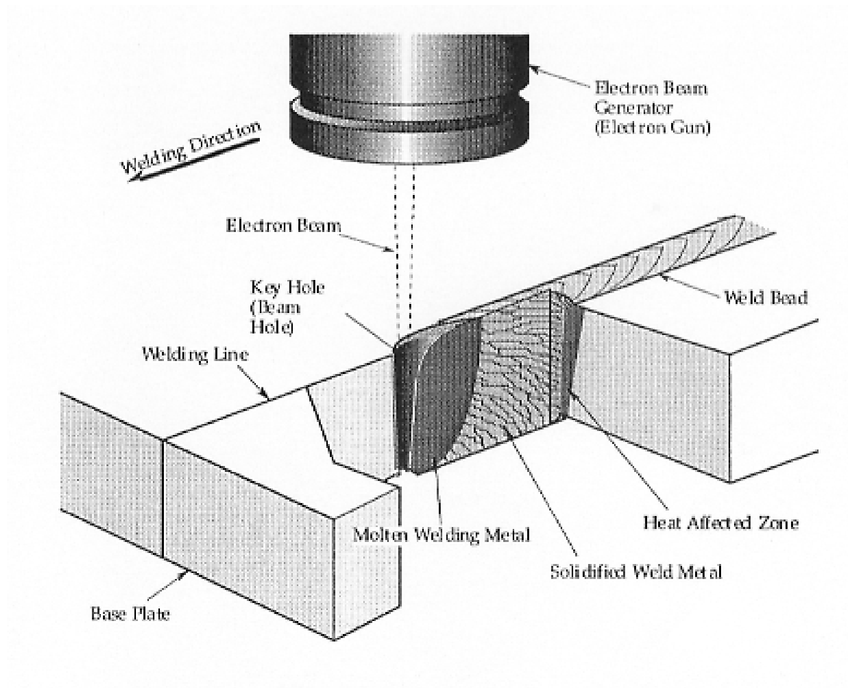


Figure 7: The electron beam welding process [7]

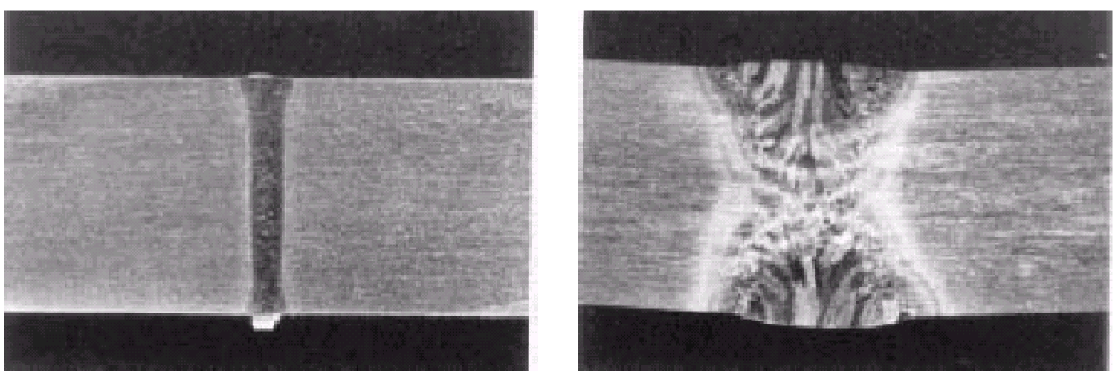


Figure 8: Cross sections of welds performed with EBW (left) and GTAW (right) [6]

On July 17, 1984, Svetlana Savitskaya, became the first woman to do a space walk and with her partner Vladimir Dzhanibekov, conducted welding experiments for over three hours outside the Soviet space station Salyut 7. In Figure 9, Svetlana Savitskaya is seen using the UHT in this specific EVA.

An interesting point about EBW is that the process on earth is automated, because of the high energy density. In space on the other hand, the process is manual (UHT) and for that reason a defocused electron beam is used.

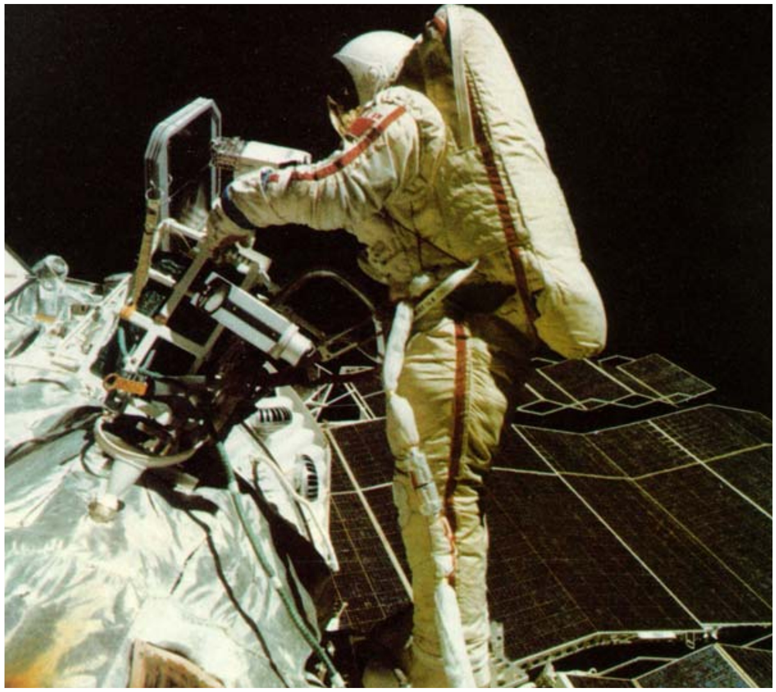


Figure 9: Svetlana Savitskaya welds in her first EVA, using the UHT

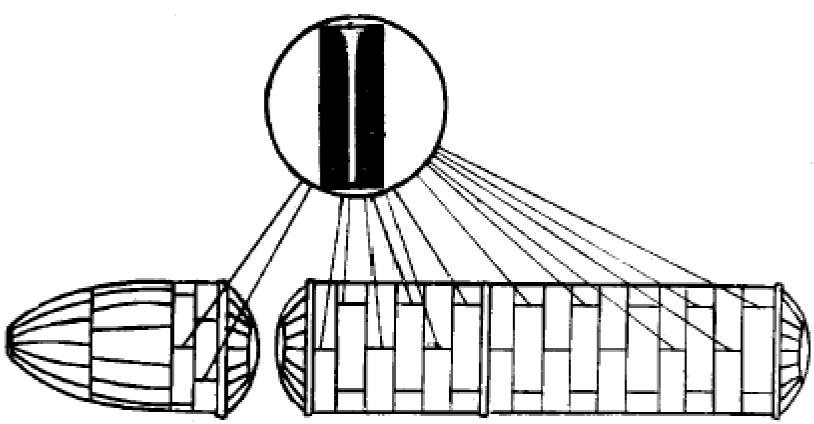


Figure 10: Arrangement of Longitudinal EB welds on fuel tanks of Energia carrier [12]

3.4 Friction Welding Processes

3.4.1 Friction Welding (FW)

In this process, the joining of the metals is achieved through mechanical friction. The welds are made by holding a non-rotating work piece in contact with the rotating work piece under constant or gradually increasing pressure, until the interface reaches welding temperature and then stopping rotation to complete the weld. The joint geometry is restricted to one flat piece and one piece that is the body of revolution. Since there is no melting, defects associated with melting-solidification phenomena are not present and unions are as strong as the base metal can be made. This process is used for the joining of aluminum landing gear components. Linear friction welding was considered by General Electric and Pratt & Whitney as an alternative for the manufacture and repair of high temperature alloy blisks for jet engines [6].

3.4.2 Friction Stir Welding (FSW)

A variation on the FW method is friction stir welding (FSW), invented by The Welding Institute (TWI) in 1991. This solid-state process joins metals through mechanical deformation. In this process, a cylindrical, shouldered tool with a profiled probe is rotated and slowly plunged into the joint line between two pieces of sheet or plate materials, which are butted together, as shown in Figure 11. This process can weld previously unweldable aluminum alloys such as 2xxx and 7xxx series. The strength of the weld is 30% - 50% higher than that of arc welding [13]. The fatigue life is comparable to that of riveted panels, because the improvement from the absence of holes is compensated by the presence of a small HAZ, residual stresses, and micro structural modifications in the welding zone [14].

As friction stir welding becomes better established it can replace plasma arc welding (PAW) and electron beam welding (EBW) in some specific applications in aluminum and titanium respectively [6]. This process is not suitable for manual application.

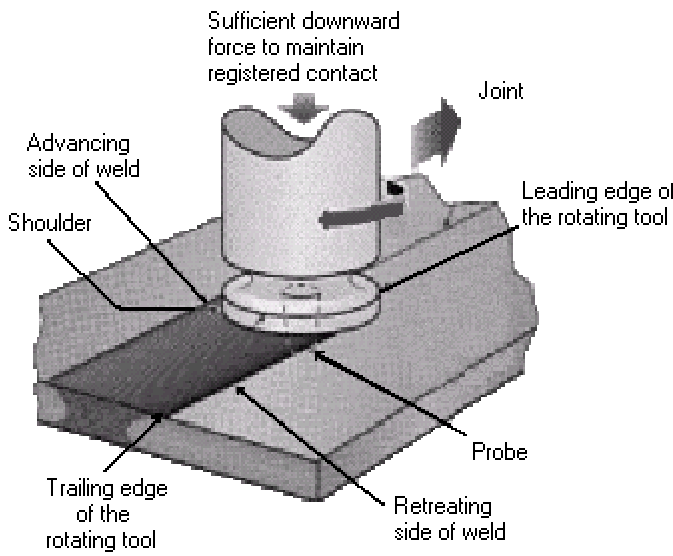


Figure 11: The Friction Stir Welding (FSW) Process.

3.5 Resistance Welding (RW)

Resistance welding includes a group of processes in which heat is generated by the resistance to the flow of electrical current through the parts being joined. It is usually used to weld two overlapping sheets, which have different thickness [15]. A pair of electrodes conducts electrical current to the joint. The resistance to the flow of current heats the surfaces, forming a weld. These electrodes clamp the sheets under pressure to provide good electrical contact and to contain the metal in the joint. The contact surfaces must be clean to obtain uniform weld size and soundness.

There are three major resistance-welding processes: spot welding (RSW), projection welding (RPW), and seam tracking (RSEW). The disadvantage of all three processes is that they require access from both sides of the weld.

Resistance welding is seldom applied in the aeronautic industry due to its occasional lack of reliability and its limitations for the joining of aluminum alloys. General Electric developed a variant of RSW, in which the displacement of the electrodes can be measured with a tolerance of 1 mm, thus significantly increasing the quality of the process. Inconel 625 (a nickel-chromium-molybdenum alloy with an addition of niobium) and Inconel 718 (a nickel-chromium alloy containing significant amounts of iron, niobium, and molybdenum along with lesser amounts of aluminum and titanium) sheets in afterburners of military jet engines are joined by RSW [16].

3.6 Brazing (B)

Brazing is a group of joining processes, which produces coalescence of materials by heating them to a suitable temperature and by using filler metal having a liquidus above 840^{o}F (450^{o}C) but below the solidus of the base metal.

The filler metal is distributed between the closely fitted surfaces of the joint by capillary attraction [17].

Thus brazing must meet each of the three following criteria:

1. The parts must be joined without melting the base metals.
2. The filler metal must have a liquidus temperature above 840^{o}F (450^{o}C).
3. The filler metal must wet the base metal surfaces and be drawn into or held in the joint by capillary attraction.

Capillary attraction is the phenomenon by which adhesion between the molten filler metal and the base metals, together with surface tension of the molten filler metal, causes distribution of the filler metal between the properly fitted surfaces of the joint to be brazed.

Brazing processes are customarily designated according to the sources or methods of heating. Current industrial methods include the following:

1. **Torch Brazing (TB)** is accomplished by heating the parts to be brazed with one or more oxyfuel gas torches using various fuels.
2. **Furnace Brazing (FB)** uses a furnace to heat prefluxed or precleaned parts with the filler metal preplaced at the joints.
3. **Induction Brazing (IB)** involves heat obtained from resistance to a high-frequency current induced in the part to be brazed.
4. **Dip Brazing (DB)** is performed in a molten salt or molten bath. Both types of bath are heated in suitable pots to furnish the heat necessary for brazing, provide protection from oxidation, and fluxing action if suitable salts are used.

5. **Infrared Brazing (IRB)** uses a high intensity quartz lamp as the source of heat. The process is particularly suited to the brazing of very thin materials.

4. Comparative Analysis of Welding Processes

In order to have a better understanding of the welding processes and how they are best suited for use in the space environment a brief comparative analysis is conducted. Table 5 summarizes a comparative analysis of some welding processes examined for welding in the space environment. The current analysis expands previous work by J.K.Watson [18] in 1988, by including parameters not included before, such as equipment cost, equipment weight, equipment power requirements and heat source intensity for each welding process. Finally, it was realized that inspectability requires special attention, thus Non Destructive Testing (NDT) in the space environment is addressed in Chapter 5.

In Table 5, various factors are considered for the different types of welding methods selected. A brief analysis of each performance factor gives a more detailed understanding of the ability of each welding process to be effectively used in the space environment. In the same Table 5, the words "Possible", "Yes" and "No" are being used. "Possible" means that the processes could be used, although it might need modification, and has not been test proven yet in the space environment. On the other hand, it might have been test proven in space environment simulators. "Yes" means that the process has been test proven in the actual space environment. "No" simply means that the process could not be used in the space environment.

4.1 IVA (Intravehicular Activity) Capability.

Most of the welding processes may be used in a pressurized (1 atmosphere), oxidizing environment as long as suitable inert gas shielding is provided to protect the hot weld metal from oxidation. The primary exception is electron-beam welding. EBW requires a high vacuum ($\sim 10^{-4}$ mm Hg) to avoid dissipation of the kinetic energy of the highly accelerated electron beam. Thus, electron-beam welding will probably not be the process of choice for IVA welding. One concern associated with the use of inert gas welding processes is the introduction of the inert gas into the closed atmosphere. While argon and helium are not toxic, excessive introduction could lower the oxygen partial pressure to dangerous levels. Either some means of removing these gases from the atmosphere must be implemented or other, more easily removed gases must be employed. Thus, all the processes, except EBW may be used in an IVA.

4.2 EVA (Extravehicular Activity) Capability

The most significant difference between the IVA and EVA environments is the lack of any substantial atmospheric pressure in the latter. Electron-beam welding , laser welding, and brazing are well suited to such conditions; arc welding processes will require modifications. For example, GTAW was modified to GHTAW in Japan so that the process could be used in vacuum. After the appropriate experimentation, it was proven that this is possible [19].

4.3 Efficiency

Efficiency is defined as the ratio of the energy actually transferred to the work piece to the energy produced by the power source (plug power). For the arc welding processes the efficiency (also known as arc efficiency) varies from 20 % to 85 % [15]. It is lowest in tungsten arc welding and higher in gas metal arc welding. In electron beam welding, the efficiency of energy transfer depends on the base material and the geometry of the point of impingement of the electron beam on the surface of the material. For example, the efficiency for EBW of steel at the start of the weld is about 60%, and increases to 90% to 95% during welding, once the vapor capillary or “keyhole” has been formed [20]. In laser beam, the efficiency of the energy transfer from the laser beam to the work piece is usually not as high as that of electron beam welding, because of the reflective nature of molten metals.

4.4 Versatility.

Versatility is defined as the extent, to which each welding method is flexible in different environments, for instance use in EVAs or IVAs. Another example is EB, which is limited to EVA activities, thus not being as versatile. In addition, in every EVA, the operator has to perform EBW while wearing a space suit, which is movement restricting.

4.5 Automation

Some welding processes can be manual, while others require automation. The high intensity processes, such as laser and electron beam welding, have a dwell time smaller than the human time of reaction (approximately 0.3 seconds) and thus require automation, as shown in Figure 12. Welding processes that advance at a relatively slow rate (<10 inches per minute) and for which extreme path-following precision is not required may be performed manually. Examples of processes of this type are gas metal-arc welding and gas tungsten-arc welding. Other processes, such as laser and electron beam, which can advance quite rapidly (30 - 100 inches per minute) and for which precision is generally critical, require some form of automation. On the other hand, EBW welding is currently manual by the use of UHT and defocused electron beam.

4.6 Heat Source Density

The heat sources for all fusion-welding processes lie between approximately 10^3 and 10^6 watts/cm^2 on the power density spectrum, as indicated in Figure 14. Sources that are more diffuse do not melt the metal, and more intense sources cause excessive evaporation. The ratio of depth to width (d/w) of the weld pool increases dramatically with the intensity of the heat source, making the welding process faster, and more efficient. Concentrated heat sources create a significantly smaller heat affected zone with lower post-weld distortions. At high heat intensities, nearly all of the heat is used to melt the material and little is wasted in preheating the surroundings. Thus, as the heat intensity decreases, the efficiency is reduced. Figure 13, displays a graphical representation of the ranking of the welding processes according to their heat source density.

4.7 Radiation (x-rays, optical)

High voltage electron-beam welding produces x-radiation as a result of inelastic collisions between the accelerated electrons and the atoms of the target material. Personnel must be shielded from this hazard. This concern is unique to high voltage electron-beam welding. Electron-beam welding can also be done with lower voltage, higher current beams. In this case, the hazard can be significantly reduced. In addition, all of the arc welding processes and laser welding require protection of the eyes from harmful radiation at optical and near-optical wavelengths. This protection is easily provided with appropriate goggles and, or welding masks.

4.8 Equipment weight

The weight of the equipment used in each welding process varies considerably according to the process as well as the specifications of the pieces to be welded. For this reason, since the usual thickness of the materials in the space environment is between one and ten mm, we consider the weight of the equipment needed to weld such thickness. Thus, the equipment weight goes form 20 Kg for brazing processes, 50Kg for resistance welding and arc processes, up to 500Kg for laser and electron beam processes. The data was found from various websites of companies making welding equipment (i.e. Lincoln Electric, Hobart, Linde and Miller). All these data is for equipment used in the Earth environment. The construction of possible welding equipment to be used in space will involve different processes and materials, thus lowering the weight (i.e. the light electron beam gun that was used on Salyut 7). The weight of vacuum chamber needed for EBW used in an IVA is not included.

4.9 Power Requirements

The power requirements were also based on data for the various processes applied on Earth. In this case, though, the data should not be altered considerably for the same processes applied in space. In space as well on Earth, the workpiece has to accept the same amount of heat in order to melt and the weld to occur. In the space environment, arc-welding processes might be more efficient but the amount of heat needed should be roughly the same.

ISSUE	PROCESS						
	BRAZING	**RESISTANCE WELDING**	**GTAW**	**GMAW**	**PAW**	**LASER WELDING**	**EB WELDING**
IVA Capability	**Yes**	Possible	Yes	Yes	Yes	Possible	No
EVA Capability	**Possible**	Possible	Yes	No	Possible	Possible	Yes
Efficiency	Low	Medium-High	20 – 75%	60 – 85%	20-75%	< 10%	90 – 95%
Versatility	Limited	Limited	Very High	Moderate	High	Moderate	Limited to EVA
Automation	Possible	Usually	Possible	Possible	Possible	Required	Usually
Heat Source Density (W/m^2)	N/A	10^5	10^4	10^4	10^5	10^6	10^6
Radiation	None	None	Eye Protection required	Eye Protection required	Eye Protection required	Eye Protection required	Shielding for X-ray Required
Weight of Equipment	1- 20Kg	10 – 50Kg	5 – 50Kg	5 – 50Kg	5 – 50Kg	100 – 500Kg	50 – 500Kg
Power Requirements	< 10Kw	1 – 10Kw	5 – 20Kw	5 – 20Kw	5 – 20Kw	10 – 20Kw	1 –10Kw
Approx. Equipment Cost		$100,000	$10,000	$10,000	$100,000	$1M	$1M
Other Advantages	Demonstrated on orbit	-Requires less skill to perform than arc welding	-Fit-up tolerant -Process control possible	Demonstrated in orbit	Demonstrated in orbit	-High d/w ratio -Low distortion	-High d/w ratio -Demo on orbit -Low distortion
Other Disadvantages	-High degree of manual skill required	-Two-side access required -Electric shock hazard	-Inert gas required -High degree of manual skill required	-High degree of manual skill required -Fumes and gases during welding	-High degree of manual skill required for the keyhole welding technique	-Manipulation -Limited fit-up constraints -Reflection problems	-Vacuum required -Distorted by magnetic fields

Table 5: Comparative analysis of different welding processes

4.10 Cost

The benefits brought by a more concentrated heat source come at a price which has to be considered mainly for fabrication purposes in space: the capital cost of the equipment is roughly proportional to the intensity of the heat source.

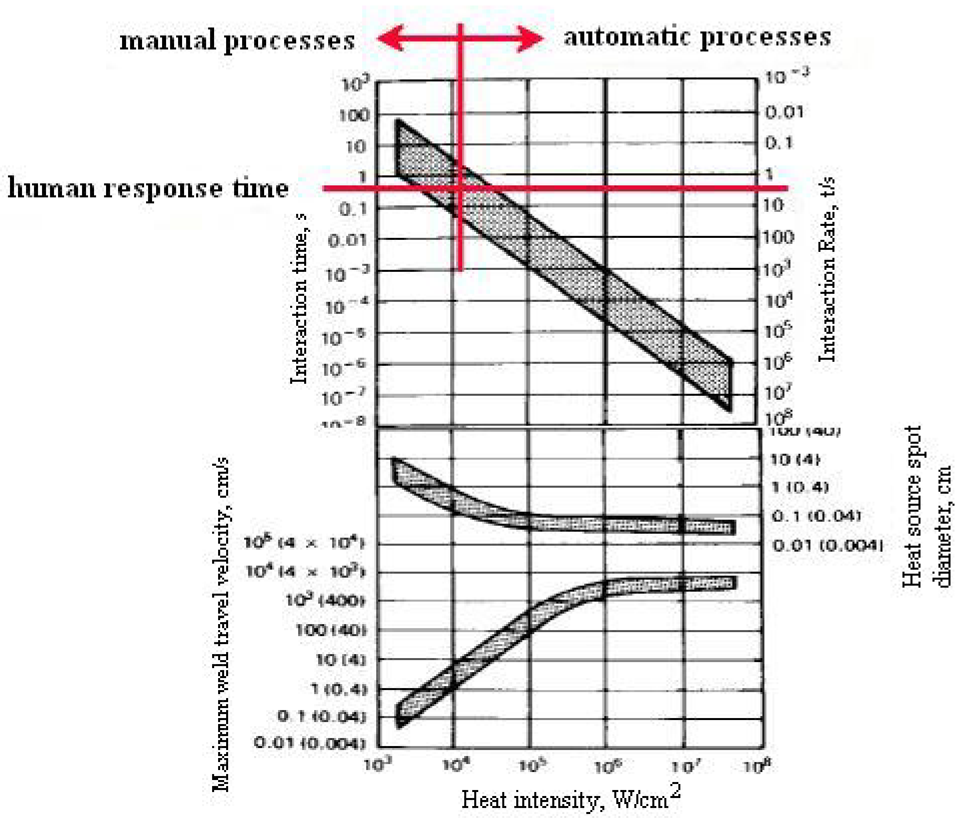


Figure 12 Maximum weld travel velocity, heat source spot, and interaction time as a function of intensity of the heat source [21]

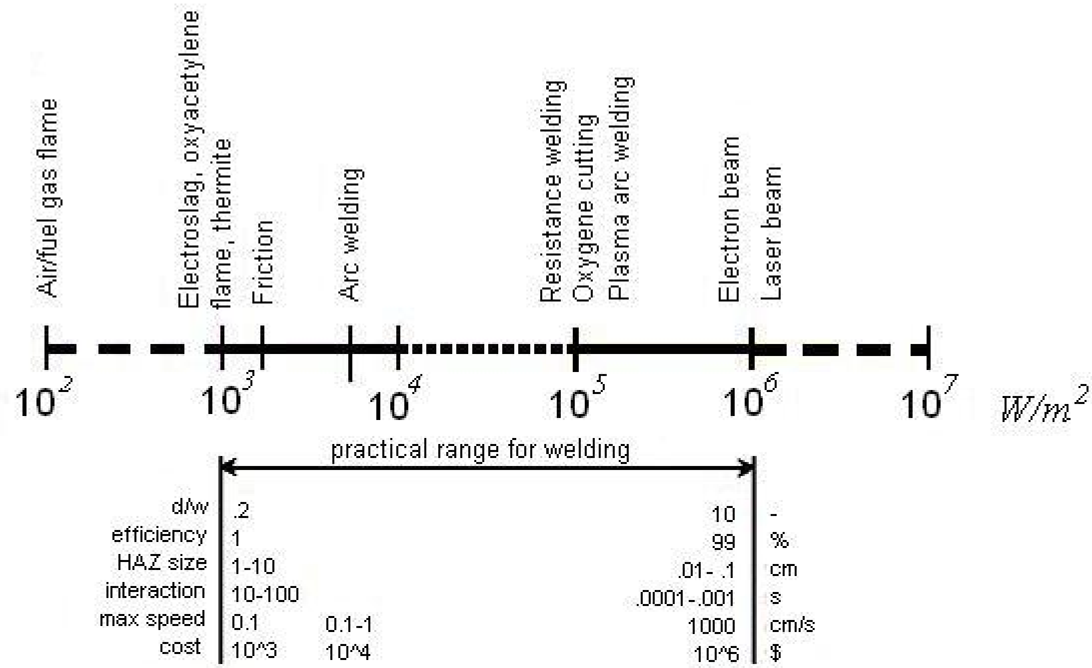


Figure 13: Welding processes ranked according to heat source density [21]

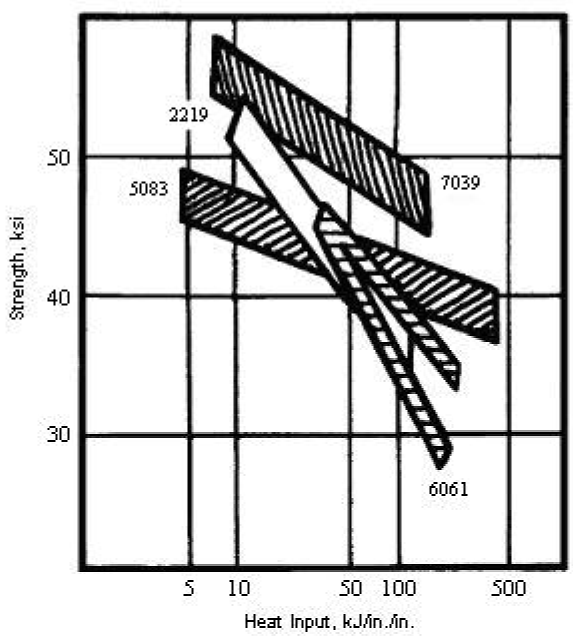


Figure 14: Heat input vs. weld strength for fusion welding [21]

4.11 Advantages

It is true that no equipment is proven to work satisfactory unless it has been tested in the environment that it is supposed to operate. Thus, it is obvious that the welding processes, which have been tested in the space environment in the past, have an inherent advantage over the others. Of the mentioned welding processes, brazing, GMAW, PAW, and EBW have been tested in space. All other advantages concern the distortion each process makes on the parent metal, the d/w ratio, etc.

4.12 Disadvanages

One of the advantages that are mainly examined concern the degree of manual skill required for each process. Astronauts are not skilled welders, but welding is something that they might be asked to do. Also examined are the use of gases, the need to have two-sided access, and finally the need of atmospheric pressure.

4.13 Summary

All of the above-examined welding processes offer various advantages as well as disadvantages for the range of applications needed for welding in space. It does not seem that one single process could satisfy the requirements needed to weld in all environments and in every different case. Instead, a variety of welding processes should be used to suit the various applications in space. For instance, the most suitable application for an EVA weld might be the EBW, followed by GTAW with the modification to GHTAW. On the other hand, for an IVA all the other processes, except EBW, could be used.

Other considerations may rule out completely one of the processes. For instance, the need to have access to both sides of the weld in order to use resistance welding might prohibit the selection of the particular process for use in the space environment. In the case that the selection had to be narrowed down to two process (one for EVAs and one for IVAs) the most appropriate might be: EBW for any kind of Extra Vehicular Activity (repair or fabrication) and GTAW for maintenance and repair during an Intra Vehicular Activity.

5. Non Destructive Testing (NDT) Analysis

One of the requirements of space structures is to have a sufficient life to provide economical exposure time in the space environment. Unfortunately, space structures are not only complicated but in most cases they cannot be shut down for repair; their maintenance and repair has to be done while working. That is one of the main reasons that preventive maintenance is crucial.

For a weld to have the required reliability throughout its life, it must have a sufficient level of quality or fitness for purpose. For welds on earth, quality is often governed by codes, specifications or regulations based on rational assessment of both economics and safety. Most of the above is experiential. In the space environment, the quality requirements are especially strict; therefore, welds that might be considered adequate on earth might not be adequate for space.

Previous work done on non-destructive testing (NDT) techniques [22-27] for the space environment involves mostly an evaluation of NDT as a monitoring process of the space structures rather than the welds. The reason is simple: welding has not yet been used as a fabrication process in space. For example, in the International Space Station (ISS), only mechanical joints will be used for erection. Welding is not considered for the assembly, even though it could save considerable weight.

Potential non-destructive techniques used in the space environment must account for the unique characteristics of the environment as well as the different welding techniques that will be used. In this part of the thesis, we will deal with the analysis of earth-bounded NDT techniques and how they can be applied in the space environment.

An analysis of the space environment and its unique characteristics is given and an original qualitative analysis of the current NDT processes is done in order to examine the possibility of use in space.

5.1 Effect of the Space Environment on NDT Methods

Nondestructive testing as well as any other activity in space faces all the peculiarities of the environment in space. The most important features of the space environment that make it unique are: a) zero gravity, b) vacuum, c) radiation, and d) composition of the residual atmosphere. All the above factors have to be accounted in order to select an earth-bounded NDT process for use in the space environment.

5.1.1 Zero Gravity Condition

Strictly speaking, in space there are never zero gravity conditions (the condition under which the forces acting on an object are zero). It is better to use the term micro-gravity characterizing the condition under which the sum of the forces acting on a body is considerably smaller than on the earth's surface. This state is usually evaluated by the value of the ratio of acceleration given to the body by the acting force (g) in relation to the force of gravitational attraction on the earth's surface (g_0). For free flying objects in space, the value of this ratio is of the order of 10^{-5} to 10^{-7} [28].Under micro-gravity conditions, a lot of the physical processes in liquid and gaseous media related to gravity driven convective flows change greatly.

5.1.2 Space Vacuum.

The mean pressure in the height range of 250-500 km is $5x10^{-4}$ Pa (~$5x10^{-9}$ Atm) [28]. The unusual features of space vacuum are the composition of the residual atmosphere and the extremely high pumping rate (diffusion rate) of gases generated in it. The pressure of the residual atmosphere surrounding space structures in low orbits is easily achieved on earth by the use of vacuum chambers. The thing that significantly differs though is the composition of the two "vacuums". The atmosphere generated in vacuum chambers on earth differs from the space atmosphere by the absence of atomic oxygen and the low mobility of molecules. In space, the content of atomic and ionized oxygen is very high and may exert a strong effect on joining of materials both during welding and in further service of joints.

Since space is an open infinite volume, the gas molecules generated at the surface of a space system rapidly move into space. Thus, the thickness of the natural residual atmosphere of space systems is very small. In addition, local pressure gradients are almost instantaneously equalized. Therefore, substances with high vapor pressure rapidly evaporate in space. That is why it is very difficult to use welding (like GTAW) or NDT methods (like penetrant) requiring gases or liquids.

5.1.3 Space Radiation

Space radiation refers to the vacuum ultraviolet radiation (VUV) of the Sun, which greatly intensifies the oxidation processes on the irradiated surfaces, as well as the radiation coming from the radiation belts of the earth.

The VUV as well as the absence of the atmosphere outside the space system are the reasons of another interesting phenomenon in space related to the wide temperature variations of the space structures. The illuminated sections of a space structure, when in the sun section, maybe heated to a temperature of 420 K (150 ^{0}C). On the other hand, when the structure is in the shadow section, it may have a temperature of 160 K (-110 ^{0}C). If any part of the structure is oriented for a long period in the same direction and is in the shadow for instance, it may have even lower temperature. Any NDT machine has to account for these temperature gradients.

5.1.4 Composition of the Space Environment

The space environment in Low Earth Orbit (LEO) (any earth orbit up to approximately 1500 Km) consists of neutral atmosphere, atomic oxygen, atomic hydrogen, meteoroids, and space debris. The content of atomic oxygen in space is responsible for the high corrosion rates of the space environment.

Atomic oxygen results from the interaction of solar radiation with oxygen. In space, the content of atomic and ionized oxygen is very high, relative to earth's atmosphere, and may exert a strong effect on the service life of the equipment.

5.2 NDT Methods

5.2.1 Visual

Visual inspection is the easiest and fastest way to inspect a weld and is the most commonly used method on earth. The technique applies to welds with discontinuities on their surface. Gross surface effects, such as severe undercut or incompletely filled grooves, can lead to immediate rejection of a weld, before any more detailed testing is undertaken. Considering these limitations as well as the necessity for quality welds in the space environment, visual methods should be used, if at all, only as a preliminary examination before the use of a more elaborate method, especially for critical joints.

5.2.2 Radiographic

In this NDT technique, x-rays, or gamma rays are used, in a manner similar to a medical x-ray to detect sub-surface flaws. The changes in density are indicated on a film, or stored digitally. Even though radiographic methods produce radiation hazards, the radiation protection of the space suits and spacecraft walls might provide sufficient protection. This is true at least for the X-ray inspection of thinner sections. The method is very sensitive and portable, and devices are readily available for earth-bound applications.

5.2.3 Ultrasonic

The ultrasonic method refers to techniques that use high frequency sound waves, which are transmitted through or reflected from objects and interfaces such as bond lines between objects. Nearly all methods of ultrasonic flaw detection use the pulse technique in which a short ultrasonic pulse is propagated from a transmitter probe, through a coupling medium, into the material under test.

Another variation of the method is the one that the transducer is not in contact with the material to be inspected (this is called airborne or non-contact technique). Airborne techniques are not suitable for EVA space applications because of the lack of atmosphere to transmit the vibrations to the workpiece.

Although vacuum and large temperature do not permit the use of common liquid couplants, in a NASA study [22-27]it was found that some space-graded compounds commonly used as lubricants are suitable for long-term use in the space environment as couplants for the ultrasonic methods. Those kinds of couplants are mainly silicone greases, or fluorinated oils.

5.2.4 Magnetic

Magnetic methods reveal structural defects through the orientation of magnetic particles on the surface of the workpiece. There are two types of earth-bounded magnetic methods: wet and dry. Wet methods are difficult to be implemented in space because they involve liquids. Perhaps, the use of low vapor pressure oils might enable its use. Because of this difficulty, these methods were ruled out of consideration in the previously mentioned NASA study as a possible NDT technique for the space environment. Dry methods should work in space as well as on earth.

5.2.5 Penetrant

There is a general agreement in the literature that liquid penetrant methods are unsuitable for NDT applications in space. These kinds of methods can only operate down to 10^{-2} torr (~10^{-5} Atm) [22], far higher pressure than existing in the residual atmosphere of space. Thus, they will not be further considered.

5.2.6 Electrical (Eddy current)

Eddy current methods are the electromagnetic method where a magnetic coil is used to include an electric current in a material. Eddy current methods are useful in surface analysis and shallow crack detection, but they are not as sensitive as ultrasonic or radiation methods for deep cracks.

5.2.7 Acoustic Emission

Acoustic emission (AE) is a different concept from the pre-mentioned methods in the sense that it is an entirely passive test (no external signal is put into the material to be tested). AE are elastic waves generated by the rapid release of energy from sources within a material, which increases as the material approaches fracture. The AE has to be detected in real time. The amount of emission produced maybe affected by the background noise. Another important phenomenon, which must be considered in the AE detection, is the Kaiser effect. This effect indicates that if a polycrystalline material, such as a metal, is stressed and then relaxed, no new AE occurs when the specimen is restressed until the previous maximum stress has been exceeded. Even though AE was one of the top candidates for structural monitoring in space use in a past study [22], taking the above into consideration, and in particular the fact that AE has to be detected as it occurs, it will not be further considered for non-destructively testing welds. This technique may apply in health monitoring of a space structure rather than in weld flaw detection.

5.3 NDT Methods Evaluation

In 1985, the NASA TRW space technology group published a final report of a nondestructive equipment study [22]. Part of the report was a table summarizing and comparing various NDT methods, mainly qualitatively. Inspired by this approach a similar comparison table (Table 7) was constructed, attempting to compare the considered NDT techniques more quantitatively. Furthermore, some different areas of comparison, not mentioned in the previous study are considered (materials, and welding techniques used in space). The visual, penetrant, and acoustic emission techniques were ruled out taking into account everything mentioned in the previous section.

In Table 2, various performance factors are considered for the four types of NDT methods selected. These factors deal with the ability that each NDT method has to detect a flaw, the materials welded in space, the geometry of the welds, the ease of operation and the user's safety. A brief analysis of each performance factor gives a more detailed understanding of the ability of each NDT process to perform an inspection in the space environment.

5.3.1 Flaw Detection:

The ability of each NDT process is examined by presenting actual values of the minimum size of a flaw that can be detected by each process as well as the maximum depth that the process is effective [15, 29]. The depth for the radiographic method is selected to have a reasonably sized, portable device, in the size of 500kV. In the ultrasonic method, the max depth needed (150mm), in order to scan for one side of the weld, was used. The magnetic method is most suitable for cracks open to the surface, while some large voids slightly in the sub-surface area might be detected. Finally the values for the eddy current method refer to the standard (37%) depth of penetration[15].

5.3.2 Materials:

The materials considered are those used for welding in space or have the potential to be used in the future (Aluminum, Titanium, Metal matrix composites, austenitic stainless steel, and martensitic stainless steel). Ultrasonic inspection of austenitic welds is difficult to perform because of the microstructure [30]. In the cooling process, after welding, large grains with a high degree of orientation may develop in the form of large elongated columnar crystals with a fibre texture. Thus, the ultrasonic velocity is different in different directions and the material exhibits much greater scattering effects. If ultrasonic flaw detection of austenitic steel welds is performed, the results will be[29]:

a) much higher attenuation, leading to loss of echo pulses;
b) much greater noise due to scattering;
c) large spurious signals due to either grain boundary reflections or to beam bending;
d) changes in the beam shape and beam path direction;

Only ferromagnetic materials could be inspected using the magnetic method, consequently, only one of the materials (Martensitic stainless steel) is not ruled out. As far as the eddy current method the only limitation is that, it can only inspect conductive materials. The radiographic method can be used in all metals.

5.3.3 Geometry of Welds:

An analysis of the weld geometry of the possible welding techniques, for welded repair and maintenance in space is performed. The assumptions made were: a) the weld geometry of the electron beam and the laser beam welding methods in keyhole mode is similar, b) various arc welding processes (gas tungsten arc welding (GTAW), metal arc welding (GMAW), plasma arc welding (PAW), and gas hollow tungsten welding (GHTAW)) also have similar weld geometries and c) the resistance welding (RW) joints made in space are similar to those on Earth. The values of the weld width and depth for each process were found using the minimum and maximum values of several welds performed in simulated space environment and cautiously relaxing the limits[31-34]. The actual geometry values for each welding process are summarized in Table 6.

	B	EBW	LW	AW	RW
Weld pool diameter or width of weld (mm)	<100	1 - 3	1 -5	5-15	5-10
Penetration (mm)	0.001-0.1	0.5-50	0.5-20	0.5-10	0.1 -1

Table 6: Summary of geometry weld values for the various processes

5.3.4 Ease of Operation:

Currently NDT technology is advanced enough to make equipment portable, light and easy to use. Problems might be encountered in the data processing procedure after the NDT method has been used. New techniques allow transfer of the results of the tests (i.e. digital x-rays or ultrasonic spectrums) to earth based stations for further interpretation.

5.3.5 Safety:

Of the NDT methods considered, the only one that raises safety considerations is the radiographic method. The inspection of thick sections, especially of steel and titanium-based alloys (this is not the case with aluminum which requires less power in order to be x-rayed), might require doses that exceed the protective capabilities of standard space suits. Since X-rays propagate in “line of sight” trajectories, simple protections, such as lead-lined walls might enable safety operation.

The following abbreviations are used in Table 7.

MMC (Metal matrix composites)
SS_1 (Austenitic stainless steel)
SS_2 (Martensitic stainless steel)

B (Brazing)

EBW (Electron beam welding)

LBW (Laser welding)

AW (Gas arc welding, metal arc welding and plasma arc welding and defocused electron beam welding)

RW (Resistance welding)

Y (Yes)

N (No)

Methods		Radiographic	Ultrasonic	Magnetic	Eddy current
Flaw Detection	Size	2% of thickness	> 1 - 5mm depending on frequency	> 0.5 mm	> 0.1 mm
	Depth	25mm SS 80mm Al	<500 mm	Surface or near surface cracks.	<13 mm SS <3.5 mm Al
Materials	Al	Y	Y	N	Y
	Ti	Y	Y	N	Y
	MMC	Y	Y	N	N
	SS_1	Y	N	N	Y
	SS_2	Y	Y	Y	Y
Geometry of welds	B	Y	N	N	N
	EBW	Y	Y	N	Y
	LBW	Y	Y	N	Y
	AW	Y	Y	N	Y
	RW	N	N	N	Y
Ease of operation		Good	Good	Good	Good
Safety		Radiation	None	None	None

Table 7: Comparative analysis of the NDT techniques considered for use in space

5.4 Summary

There are earth-bounded NDT processes that could be used in space. Nonetheless, there is not a single cure-all technique to non-destructively inspect welds or structures in space. Like on Earth, different techniques are superior in some aspects but inferior in others. This can be seen from the comparative analysis in Table 7. However, in the author's opinion, the eddy current method has the most potential. Even though radiographic and eddy current methods are both suitable for the four welding processes, the radiographic method has the drawback that heavy protective equipment (made of lead) is needed, in order to protect the users from radiation. Furthermore, eddy current is appropriate for all the other cases examined; with the exception of MMC testing. In that case, a small hand tool using ultrasounds could be used. Unfortunately, no technique could be proven reliable, unless it will actually operate in the environment that is designed for.

Finally, more work should be done as far as the comparative analysis is concerned with respect to weld defects. Every welding method generates different defects that may not necessarily be detected by a NDT method. Thus, another important performance factor that should be taken into account is how the discontinuities associated with the various welding processes preclude the use of different NDT methods.

Taking into account the previous table, as well as the fact that methods involving liquids are not suitable for EVAs, we could conclude that X-rays are well suited for EVAs and ultrasound for IVAs.

6 Generation of Defects in Micro-gravity

6.1 Description of Possible Weld Defects

Weld defects or discontinuities are interruptions in the desirable physical structure of the weld. Some of the most common defects encountered in welds are described below [35].

6.1.1 Undercut

Undercut is the effect when a groove is melted into the base metal adjacent to the toe or root of the weld and left unfilled by weld metal. In addition, in undercutting, the welding bead has parallel grooves at the side. Figure 15 displays the appearance of the undercutting mechanism in a cross section.

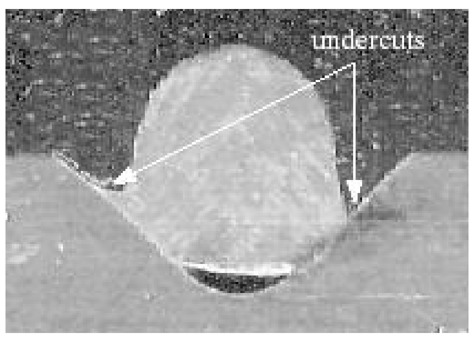


Figure 15: Undercutting mechanism [36]

6.1.2 Porosity

Porosity includes cavity-formed discontinuities formed by some type of gas entrapment during solidification. Pores can occur on the surface of the weld or just below it. Pores can be distributed throughout the weld, isolated in small groups, or concentrated at the root or the toe of the weld. Their shape might be round or elongated teardrop. Figure 16 shows transverse sections of welds, in both terrestrial and micro-gravity environments. Both welds have pores. It is clear that in the terrestrial environment the blowholes were segregated at the upper part, whereas in the space environment, blowholes were distributed uniformly in the weld.

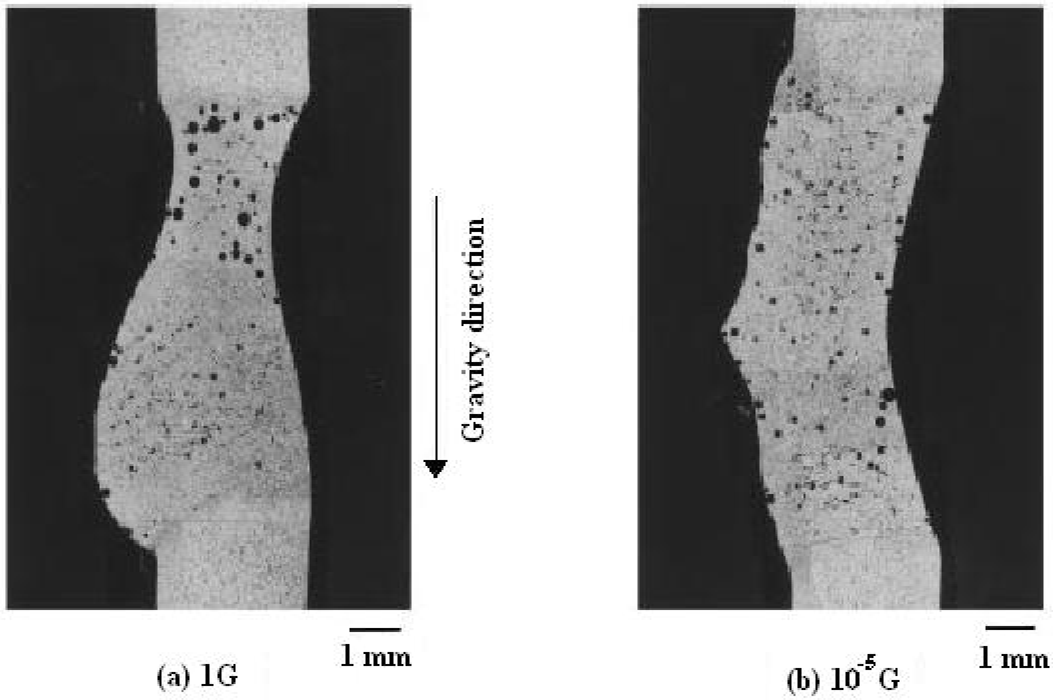


Figure 16: Transverse sections of bead-on-plate welds welding [37]

6.1.3 Tunnel Porosity

Tunnel porosity is a defect in which an open channel, which remains unfilled with weld metal, is formed at the root. An example that leads to tunnel porosity is when the two liquid regions on each side of the weld pool collapse on each other, giving the surface aspect of an acceptable weld. However, the bottom of the weld pool solidified prematurely preventing wetting by the molten metal. In this case, the defect is continuous. Such a case can be observed in Figure 17.

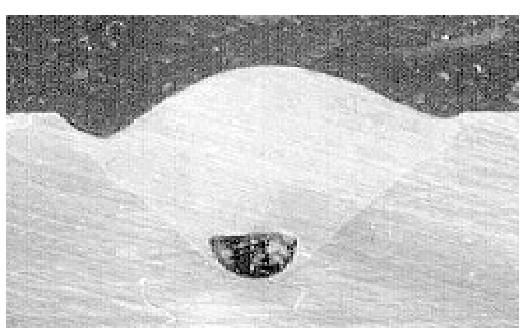


Figure 17: Tunnel porosity in GTAW [36]

6.1.4 Slag inclusions

The defect of slag inclusions involves the case of nonmetallic solid material entrapped in the weld metal or between the weld metal and the base metal. It may occur when using welding processes that employ a slag covering for shielding purposes. During welding, slag may spill ahead of the arc and subsequently be covered by the weld. Slag trapped in this manner is generally located near the root. Radical motions of the electrode, such as wide weaving, may also cause slag entrapment on the sides or near the top of the weld, after the slag spills into a portion of the joint that has not been filled by the molten pool. The lack of gravity in space would prevent inclusions from floating to the surface.

6.1.5 Lack of Penetration

Lack of penetration is the condition in which the penetration on the joint is not adequate.

6.1.5 Humping

Humping, is also called beading, and presents a weld bead with an irregular surface contour consisting of a series of bead-like protuberances, as shown in Figure 18. In this figure, the top figure is a top view of the humped weld seam, the bottom left picture is a cross section of the bead-like protuberance (cross section A-A), and the bottom right is a cross section of the void between beads (cross section B-B).

In a split bead, the weld seam is split into two independent parallel seams, which are separated by an empty channel in between. Parallel humping is a type of split bead in which the parallel seams are humped Figure 19.

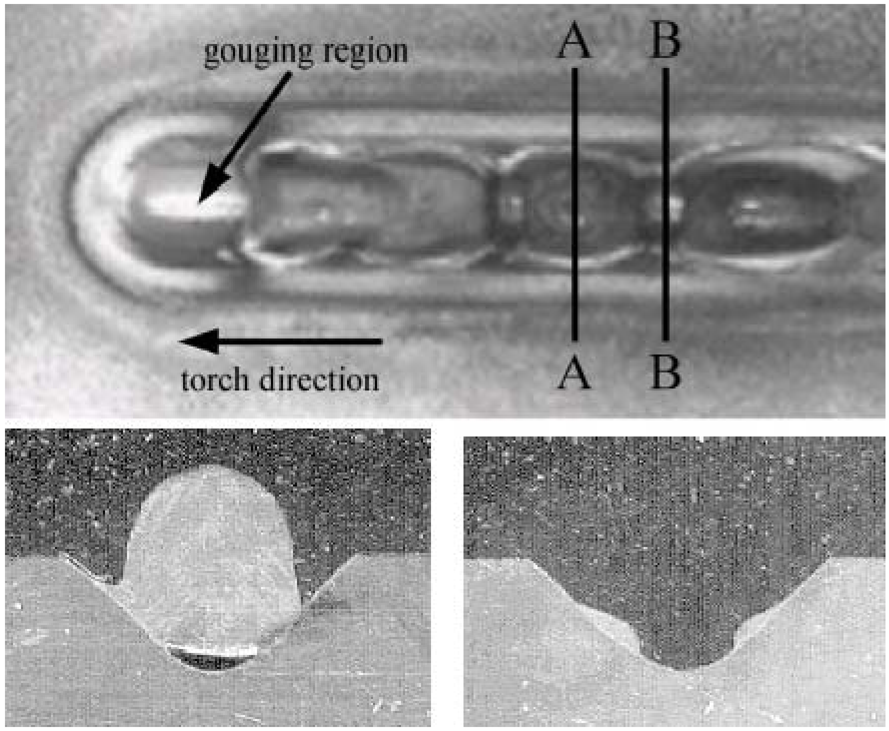


Figure 18: Humping in the GTAW [36]

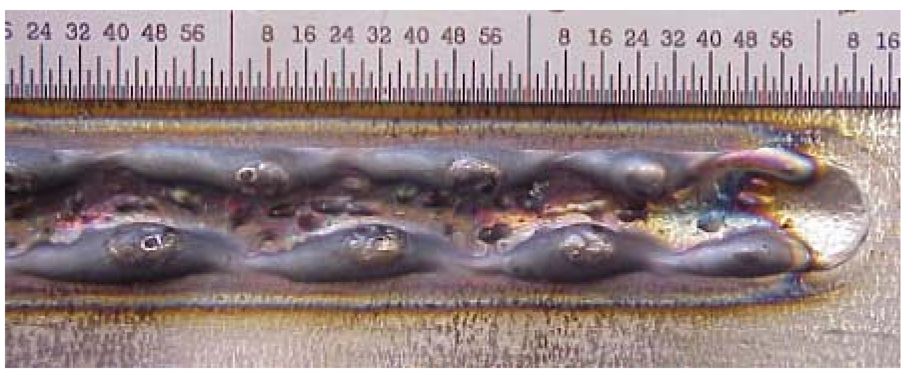


Figure 19: Parallel humping in the GTAW [36]

6.2 Effect of Gravity on Generation of Humping in High Current GTAW.

In this part of the thesis, we are going to analyze the impact of gravity in the generation of humping. The procedure used is based on a paper written by Mendez and Eagar [36]. The model presented in that paper was reproduced and a different case was examined by setting gravity to zero to simulate the environment in space (IVA) and compare the results with these obtained for the Earth's atmosphere. More specifically, we are going to analyze how gravity affects the formation of humping on a weld made using GTAW.

At present, welding productivity is not an issue of great concern in the area of welding in space, since there is no welding performed in the space environment since 1984. In the future, the issue will definitely be in the scientists mind. Welding productivity can be improved by increasing the welding speed as well as the current. In these cases, though the presence of various discontinuities (humping, tunnel porosity, undercutting, etc) is often unavoidable.

The generation of humping can be analyzed using the capillary instability theory in a long liquid body [38-40]. The capillary instability theory states that humping will occur only when apparent contact angle (θ, Figure 20), is larger than 90^0. In this case, humping will occur only when the welding pool is longer than a critical value L_C. The expressions of L_C, based on the capillary instability theory, for different approaches, are presented in Table 8.

On the other hand, capillary instability theory cannot predict the humping in bead on plate of GTA welds, where the apparent contact angle is close to 0^0 and other arc welds, where the welding pool is not long enough to set off a capillary instability. In these cases, humping is mostly associated with a large depression of the welding pool under the arc observed at high welding currents and high welding velocities. In some publications [41, 42], the depression is also called the "gouging region".

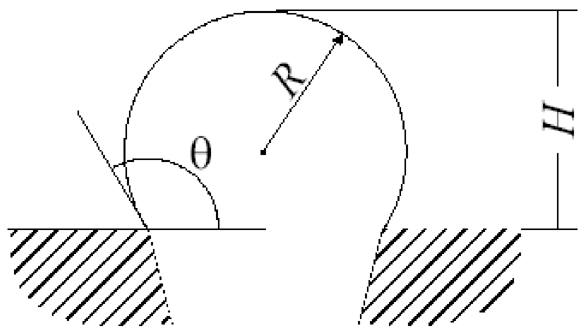


Figure 20: Cross section of a long cylinder-like fluid body [36]

6.2.1 Geometry of the Weld Pool

The cross and longitudinal views of a GTA welding pool are described in Figure 21. The figure on the upper left corner is a longitudinal section. The one on the upper right corner is a cross section; and the figure at the bottom, a top view of a weld in which the welding current was suddenly cut off.

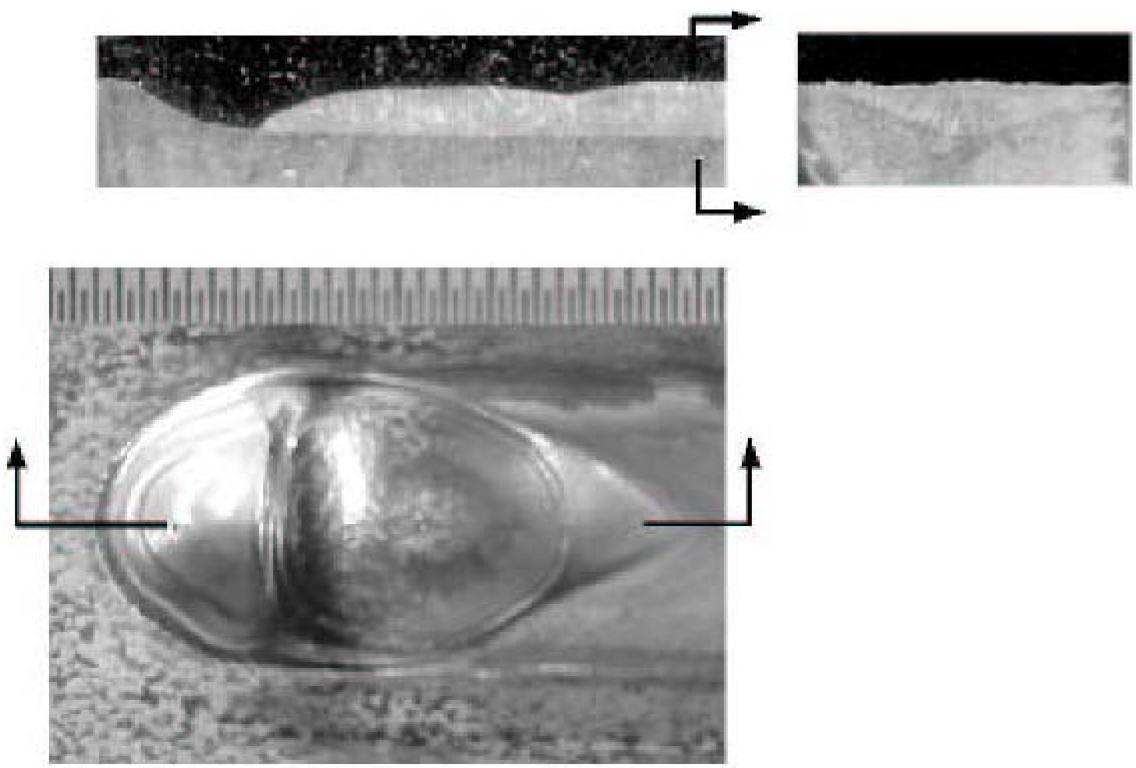


Figure 21 Weld pool at high currents and speeds [36]

Criterion	Critical length	Reference
Bradstreet	$L_C = 2\pi R$	[39]
Gratzke	$L_C = 2\pi R f(\theta)$	[38]
	$f(\theta) = (1-(\pi/2\theta)^2)^{-1/2}$	
Schiaffino	$L_C = 2\pi H g(\theta)$	[40]
	$g(\theta) = (\cos\theta(\cos\theta - 1)/\beta)^{-1/2}$	
	$B = 0.67 - 9.5\ 10^{-3}\theta + 2.36\ 10^{-4}\ \theta^2 - 4.47\ 10^{-3}\ \theta^3$	

Table 8: Capillary instability criteria.

In Figure 22 the free surface is very depressed, turning into a thin liquid film under the arc. A thicker rim of liquid runs around the edge of the weld pool carrying molten metal to the rear of the weld pool. The transition line marks the sudden change from the thin liquid film into the bulk of liquid at the rear. The most distinct characteristic of the weld pool is the deep depression of the free surface, having a "gouging region" under the arc, a "rim" of molten metal around it, and a bulk of molten metal ("trailing region") at the rear of the welding pool.

Also seen in the same figure is a "transition line," which shows the sharp transition between the gouging region and the trailing region. At the edge of humping, the trailing region receives little heat from the arc and contributes very little to weld penetration. Thus, the transition line is located at the depth of maximum penetration, where the melting interface is close to horizontal.

6.2.2 Heat Transfer

For the case of fast moving sources, the convective heat transfer in the solid dominates over conduction for both the longitudinal and the lateral direction. A heat source is considered fast when the so-called Peclet number is greater than one. The Peclet number is given by equation (1). In this equation,V is the welding

$$P_e = \frac{V \cdot L}{\alpha} \tag{1}$$

speed, L is the characteristic length of the heat source (i.e. the arc diameter) and α is the heat diffusivity of the solid base. The values of P_e for the experiments considered in this model vary from 35 to 75; thus indicating that the heat transfer problem can be approximated as one dimensional in the direction of penetration, with the following energy balance at the melting interface:

$$Q_{\alpha}(x) = \rho \cdot \Delta H_m \cdot W(x) + Q_{solid}(x) \tag{2}$$

x is the longitudinal coordinate in Figure 22, $Q_\alpha(x)$ is the heat input from the arc, ΔH_m is the latent heat of melting, W(x) is the velocity at which the melting interface advances, creating the welding penetration, and $Q_{solid}(x)$ is the heat flow from the melting interface to the solid substrate.

Equation (2) can be integrated over x, which is proportional to the residence time of the arc. If we assume a gaussian heat source with symmetry of revolution, and considering the effective diameter of the heat source as four times its standard deviation σ_Q, it is possible to estimate the average heat transfer into the solid ($\bar{Q}_{solid}$) as follows:

$$\bar{Q}_{solid} = \frac{\sqrt{2 \cdot \pi}}{4} \cdot Q_{\max} - \frac{\rho \cdot \Delta H_m \cdot D \cdot V}{4 \cdot \sigma_Q} \tag{3}$$

in equation (3) D is the depth of penetration. $\bar{Q}_{solid}$ gives an estimate of the order of magnitude of the thermal energy that diffuses into the solid .

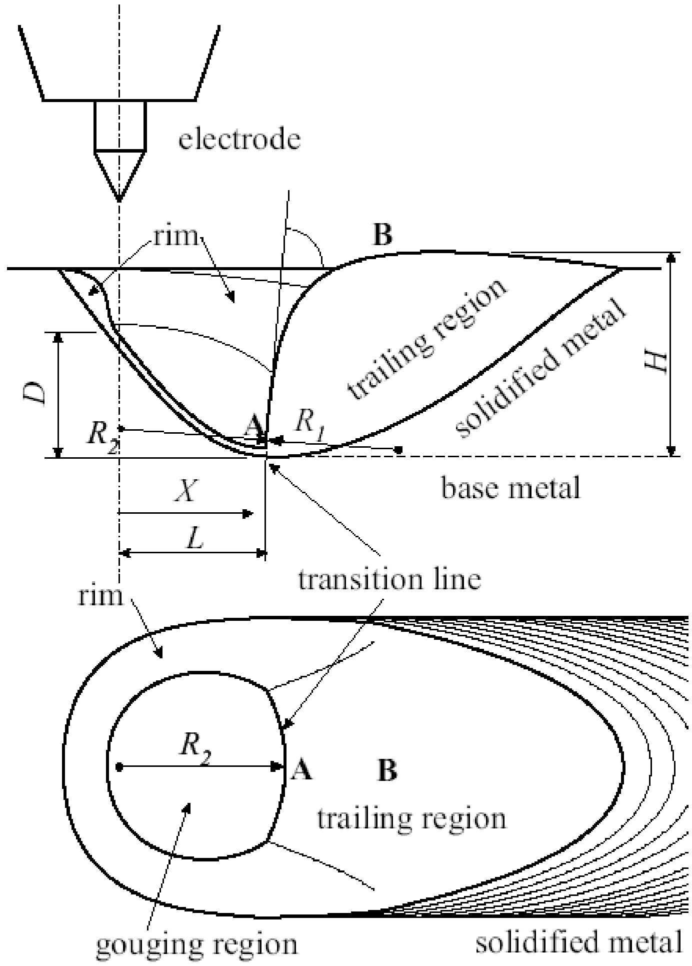


Figure 22: Schematic of weld pool in high currents and speeds [36]

6.2.3 Forces on the Transition Line

The forces acting on point A in Figure 22 are originated from hydrostatic pressure, capillary pressure, and arc pressure. The force due to the hydrostatic pressure is:

$$(P_h)_A = \rho \cdot g \cdot h \tag{4}$$

where H is the column of metal between point A and the highest point of the free surface (point B), ρ is the density of the molten metal and g is the acceleration of gravity. The capillary force (which acts over all of the free surface) at point A is:

$$(P_c)_A = \sigma \cdot (\frac{1}{R_1} + \frac{1}{R_2}) \tag{5}$$

where σ is the free tension and R_1 and R_2 are the principal curvatures of the free surface at the transition line. The radius of curvature R_1 is in the plane of symmetry and R_2 is in a plane normal to the plane of symmetry and to the free surface at point A.

The influence of the arc is expected to be minor at point B. That is why it is assumed that $\left(P_a\right)_B \approx 0$.

Other forces acting on the trailing region, such as Marangoni, electromagnetic and buoyancy, are induced by the action of the arc, which is very weak over the trailing region on the verge of humping. That is why these forces are not expected to influence the occurrence of humping.

The force balance between points A and B is as follows:

$$(P_\alpha + P_h + P_c)_A = (P_\alpha + P_c)_B \tag{6}$$

From now on whenever we refer to forces due to pressures, such as force due to arc pressure we will simply refer to them as pressures. The forces that we consider are the arc pressure (P_α), the hydrostatic pressure force (P_h), and the capillary pressure force (P_c). The forces acting at point B are very small and will not be considered, as mentioned above. The force balance can be expressed in a non-dimensional form using various scaling relationships for each different quantity.

The scaling relationships used were:

$$R_1 = \frac{H}{2 \cdot \sin^2(\theta/2)} \cdot r_1 \tag{7}$$

$$R_2 = \frac{-L}{\sin(\theta)} \cdot r_2 \tag{8}$$

$$L = L_i \cdot l \tag{9}$$

$$P_a(L) = P_{\max} \cdot p_a(l) \tag{10}$$

$$Q_a = \bar{Q}_{solid} \cdot p_a(l) \tag{11}$$

All dimensionless factors are of the order of magnitude of one. Finally using he above equations, equation (6) takes the non-dimensional form seen in equation (12).

$$p_a(l) = \frac{\rho \cdot g \cdot h}{P_{\max}} - \frac{2 \cdot \sigma \cdot \sin^2(\theta/2)}{H \cdot P_{\max} \cdot r_1} + \frac{\sigma \cdot \sin(\theta)}{L_i \cdot P_{\max} \cdot r_2 \cdot l} \tag{12}$$

In this equation, the left hand side is the normalized arc pressure and the right hand side is the hydrostatic and the capillary pressures (together representing the metal pressure). The graphical representation of the above equation can be seen in Figure 23. The curves seen in this figure represent the arc and the metal pressure as a function of the normalized size of the gouging region (l). The point where these curves intersect determines the point of equilibrium for the transition line. The arc pressure is assumed a gaussian shaped curve with the center at the beginning of the gouging region. The assumption makes sense in the way that the arc pressure at the transition line decreases with distance from the electrode.

In Figure 23, there are three metal pressure curves for three different conditions: the absence of a gouging region, the stable gouging region, and the unstable gouging region. a) When the metal pressure is higher than the arc pressure at all times, there is no gouging region. b) When the metal pressure crosses the pressure curve twice, there are two points at which the metal and arc forces are in equilibrium. One of these points is unstable (point U) and the other is stable (point S). Finally, when the metal pressure crosses the arc pressure curve only once, and then the arc pressure is always larger than the metal pressure, the crossing point is unstable. In the last case, we experience the phenomena of split bead, parallel humping, and tunnel porosity.

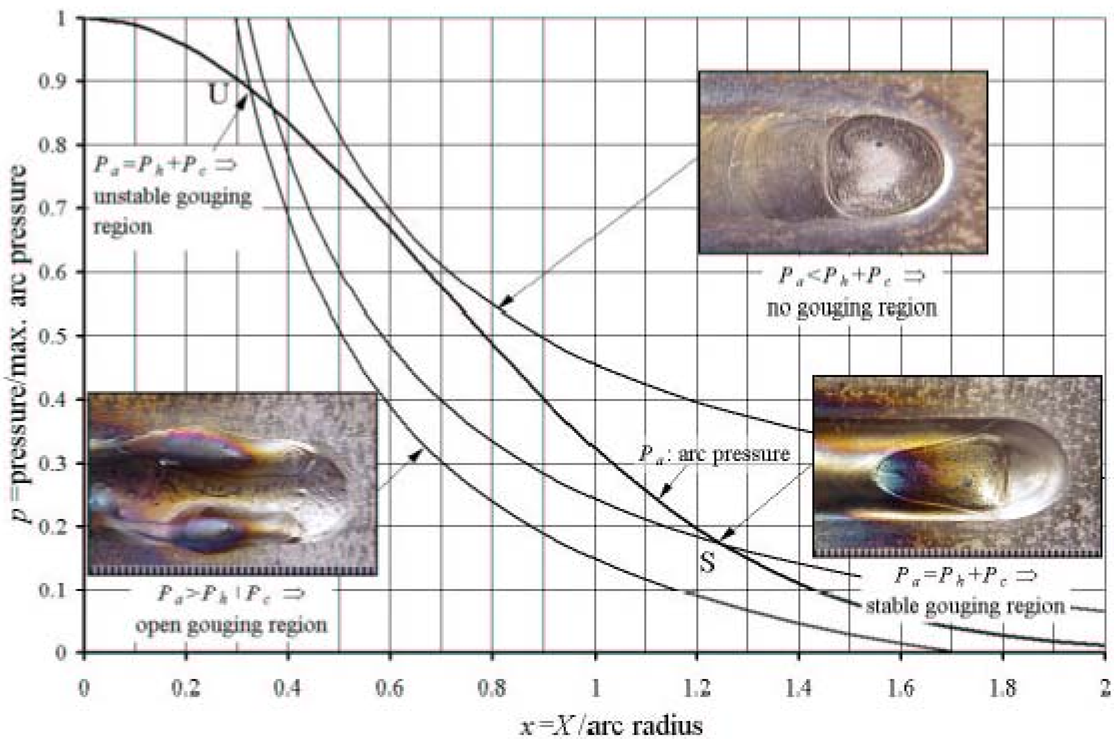


Figure 23: Stability of the gouging region [36]

6.2.4 Analysis of the Humping Mechanism Using Experimental Results

In this part of the thesis the experimental results from the work of various scientists, Savage et al [43], Tsai [44] and Lin [45], are used, in order to analyze the mechanism of humping using the model's approach. The analysis is done twice. The first time the experimental results are analyzed at atmospheric conditions and the second time at zero gravity conditions.

Due to the lack of specific measurements or models, there were some assumptions made for the analysis. More specifically:

a) The maximum arc pressure on a deformed surface was assumed to be the same as that of a flat surface
b) The distance of influence of the arc was assumed to be the arc's diameter

The gaussian distribution approximations for the arc pressure and the heat input over the flat surface are given by the following equations:

$$P_{flat}(R) = P_{\max} \cdot e^{\left(\frac{-R^2}{2\cdot\sigma^2_P}\right)} \tag{13}$$

$$Q_{flat}(R) = Q_{\max} \cdot e^{(\frac{-R^2}{2 \cdot \sigma^2_Q})} \tag{14}$$

P_{max} and Q_{max} are the maximum values of the pressure and the heat input, σ_P and σ_Q are the standard deviations of the distributions and R I the radial distance from the axis of symmetry.

Using Lin's experimental data [46], we get the following approximations:

$$P_{\max} = 32.85 \cdot I^{1.244} \cdot \alpha_e^{-0.7855} \tag{15}$$

$$\sigma_P = 1.784 \cdot 10^{-4} \cdot I^{0.2892} \cdot \alpha_e^{0.1571} \tag{16}$$

where I is the welding current, α_e the electrode tip angle.

Using Tsai's experimental data [44], we get different approximate equations:

$$Q_{\max} = 1.441 \cdot 10^{-4} \cdot I^{0.7444} \cdot L_a^{-0.7680} \tag{17}$$

$$\sigma_Q = 3.770 \cdot 10^{-3} \cdot I^{0.2645} \cdot L_a^{0.3214} \tag{18}$$

L_α is the arc length.

In the following tables, there is a summary of all the data used from Savage. The results can be seen in Figure 24. In this figure, the normalized heat input curves where calculated using equations (17) and (18), using Q_{solid} as normalization parameter. The distance of influence (L_i) was considered $4\sigma_P$. The normalized radii r_1 and r_2 were one and 0.4 respectfully. Finally, the normalized extension of the gouging region at the beginning of humping (l_{eq}) was calculated from equation (12).

S content [ppm]	*P* [Kg/m³]	*σ* [N/m]	*θ* [degrees]	*α_e* [degrees]	*ΔH_m* [J/Kg]
400	7000	1.15	90	90	2.65 10^5

Table 9: Parameters used for Figure 24

I [A]	V [mm/s]	L_α [mm]	H [mm]	P_{max} [kPa]	σ_P [mm]	Q_{max} [W/mm2]	σ_Q [mm]	Q_{solid} [W/mm2]	l_{eq} -	q_{ep} -
300	9.58	4.1	3.4	1.2	1.9	68	2.9	40	.68	1.16
350	8.39	4.4	3.9	1.4	2.0	73	3.1	44	.75	1.07
400	7.76	4.7	4.2	1.7	2.1	76	3.3	45	.81	1.01
450	6.36	5.2	5.0	1.9	2.1	78	3.5	46	.80	1.05
500	4.61	6.2	6.6	2.2	2.2	73	3.8	44	.74	1.17

Table 10: Experimental data used for Figure 24

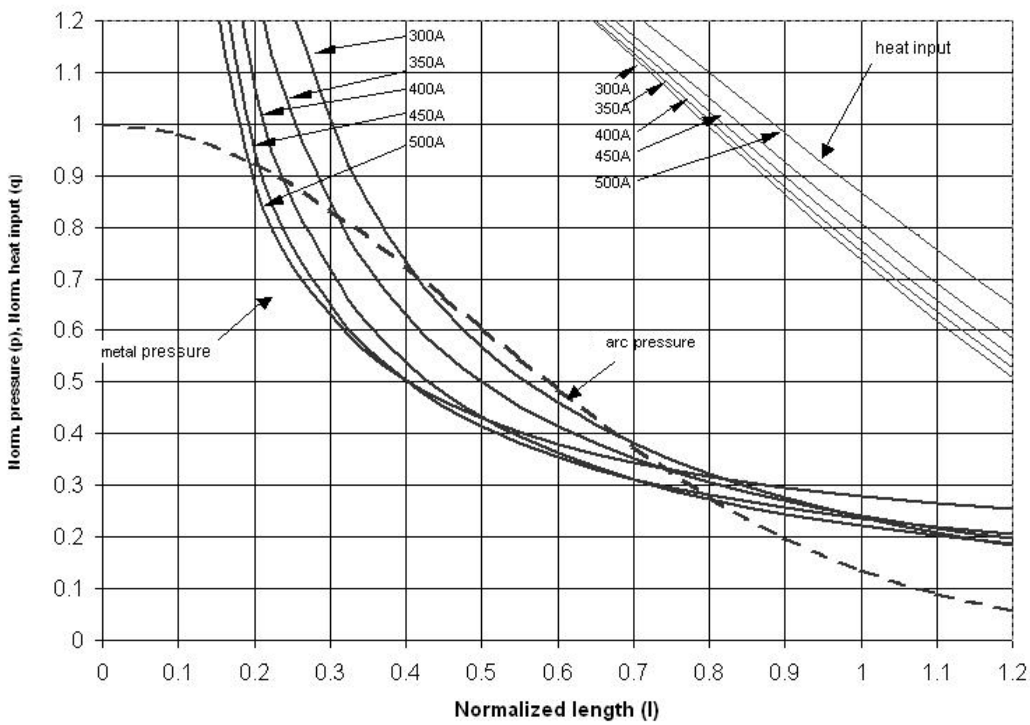


Figure 24: Force balance at the transition line at the onset of humping (Savage's data)

In the above figure we could also observe that the transition line at the onset of humping is located between approximately l=0.68 and l=0.81. The normalized heat input range for these values is 1.01 and 1.17. These results are in agreement with the hypothesis that at high currents, humping occurs when the transition line extends beyond the reach of the arc (in other words after q_α=1).

S content [ppm]	*P* [Kg/m^3]	σ [N/m}	θ [degrees]	α_e [degrees]	ΔH_m [J/Kg]
6	6900	1.82	30	60	2.65 10^5
230	6900	1.25	90	60	2.65 10^5

Table 11: Parameters used for Figure 25 and 26

S content [ppm]	*I* [A]	*V* [mm/s]	L_α [mm]	*H* [mm]	l_{eq} -	q_{eq} -
6	274	11.6	7.3	0.9	1.06	1.12
6	334	14.1	7.5	1.1	1.13	0.99
6	500	10.6	9.4	3.0	1.2	0.88
6	500	15.0	8.5	1.1	1.29	0.78
230	274	11.6	7.3	0.9	-	-
230	334	14.1	7.5	1.1	-	-
230	500	10.6	9.2	2.8	-	-
230	500	15.0	8.2	1.9	-	-

Table 12: Experimental data used for Figure 25 and 26

The data described in Figure 25 were obtained using 304 stainless steel with 6ppm sulfur content. The curves have been calculated using equation (12) and their shape is in general agreement with those of Figure 24. The normalized heat input at the transition line varies between 0.67 and 1.13. These values are consistent with the ones estimated using Savage's experiments.

The welds corresponding to Figure 26 were performed on 304 stainless steel with 230 ppm sulfur content. It is obvious that in this figure, the metal pressure is lower than the arc pressure, thus resulting in an open gouging region.

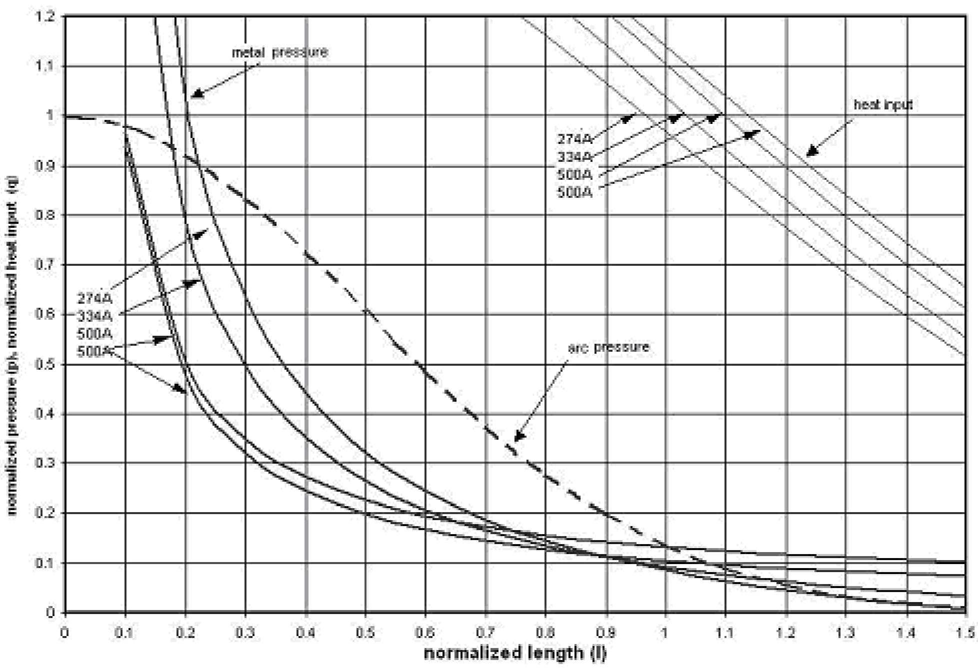


Figure 25: Force balance at the transition line at the onset of humping (data from Tables 11,12)

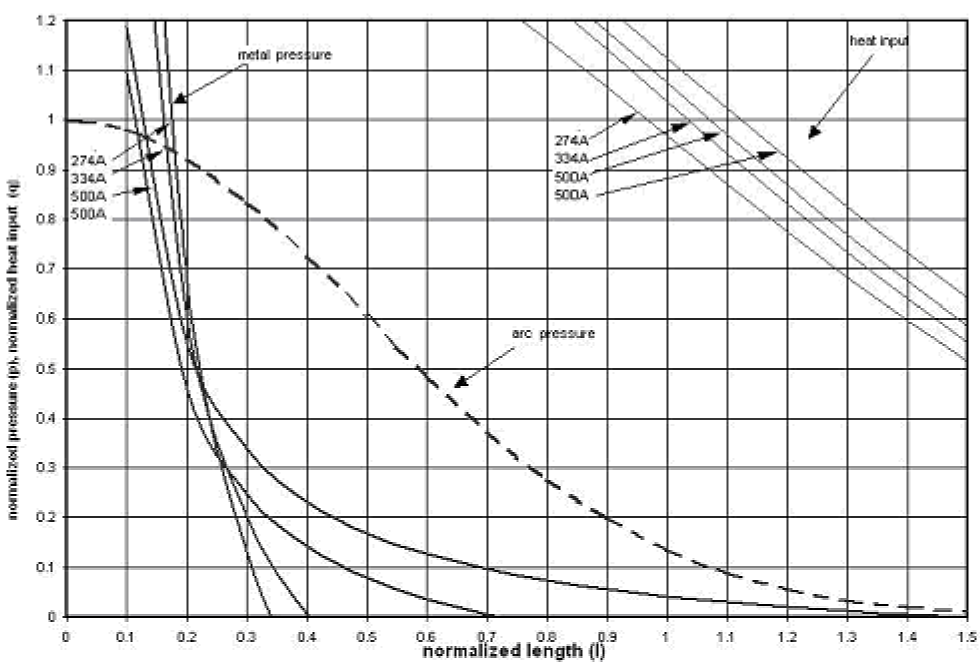


Figure 26: Force balance for open gouging region (data from Tables 11,12)

Following are figures representing the same three cases examined above with the difference that they are considered for the zero gravity condition (g=0). In Figure 27 we can clearly see that unlike the same case for $g=9.81 m/s^2$ there is an open gouging region. In this case, there is a considerable difference in the arc pressure curves, since the metal pressure is lower than the arc pressure.

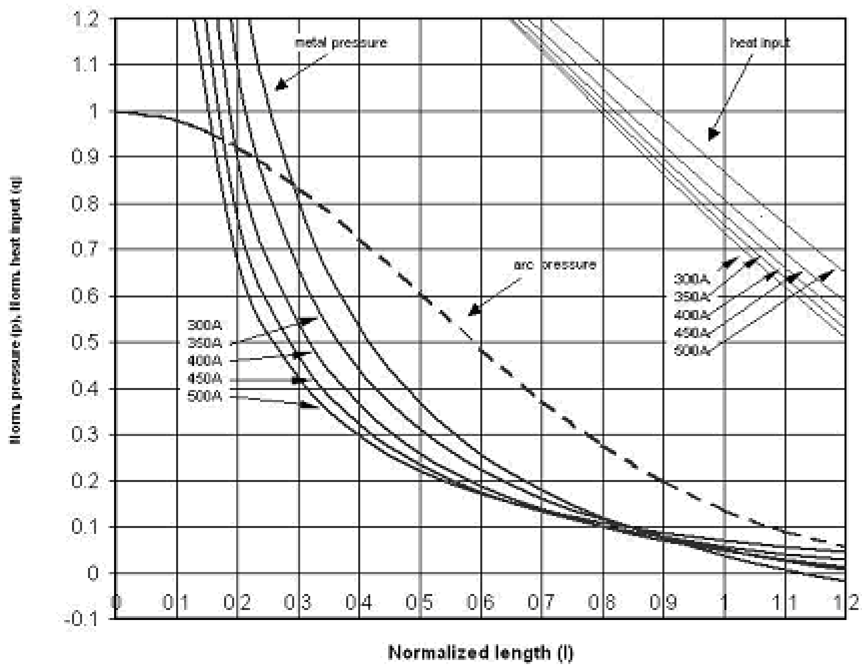


Figure 27: Force balance at the transition line (Figure 24, for g=0)

In the next two figures, gravity has a minor effect on the arc pressure curves. Specifically in Figure 28 the normalized heat, input at the transition line varies between 0.80 and 0.88, and in Figure 29 there is an open gouging region.

In order to explain the different effect that zero gravity conditions had on Savage's and Mendez's data, a more detailed analysis was performed. The reason why gravity affects the onset of humping differently in various experimental data is that the values of penetration were different in each case. The analysis performed takes into account the difference in the penetration depth (D) as well as the height of the metal column (H) in the three different experiments.

In the case of Savage's experimental data, the depth of the penetration (D), as well as the height of the metal column (H), are considerably greater than the data taken from both Mendez's experiments. Savage's welds are deeper by a factor of three. The effect that H has on the normalized arc pressure increases with the increase of the normalized length. The effect of H is much bigger on the first term of equation (12) (normalized hydrostatic pressure). Taking the above into account, when we set gravity equal to zero (g=0), the normalized hydrostatic pressure becomes zero. Consequently, the experiment that had the greater penetration is going to have the greater change in the normalized arc pressure, since the "balance" that the hydrostatic term was providing is eliminated. The details of this analysis are available in Appendix B.

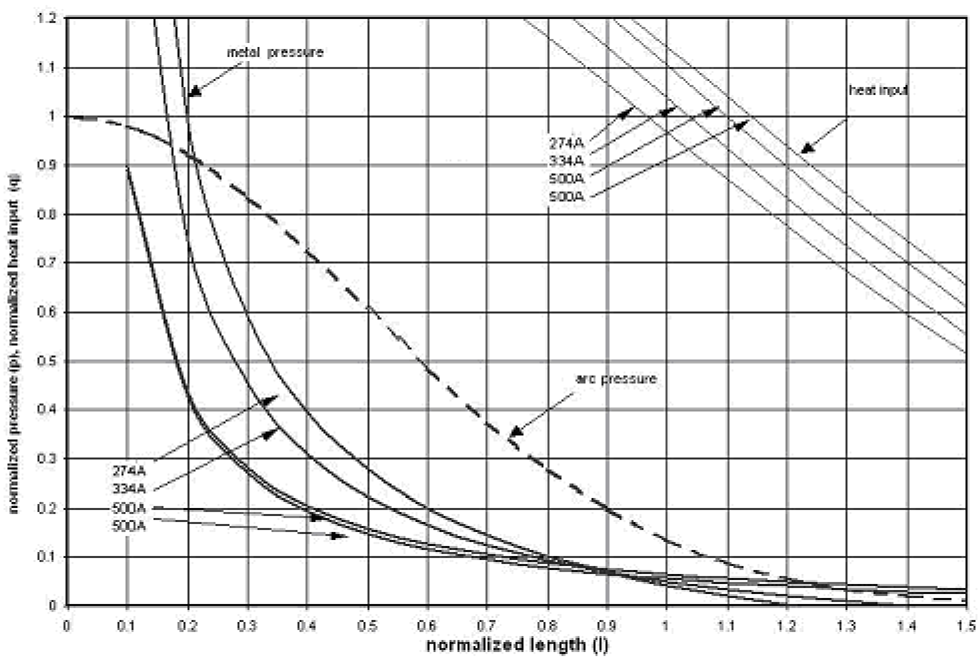


Figure 28 Force balance at the transition line (Figure 25, for g=0)

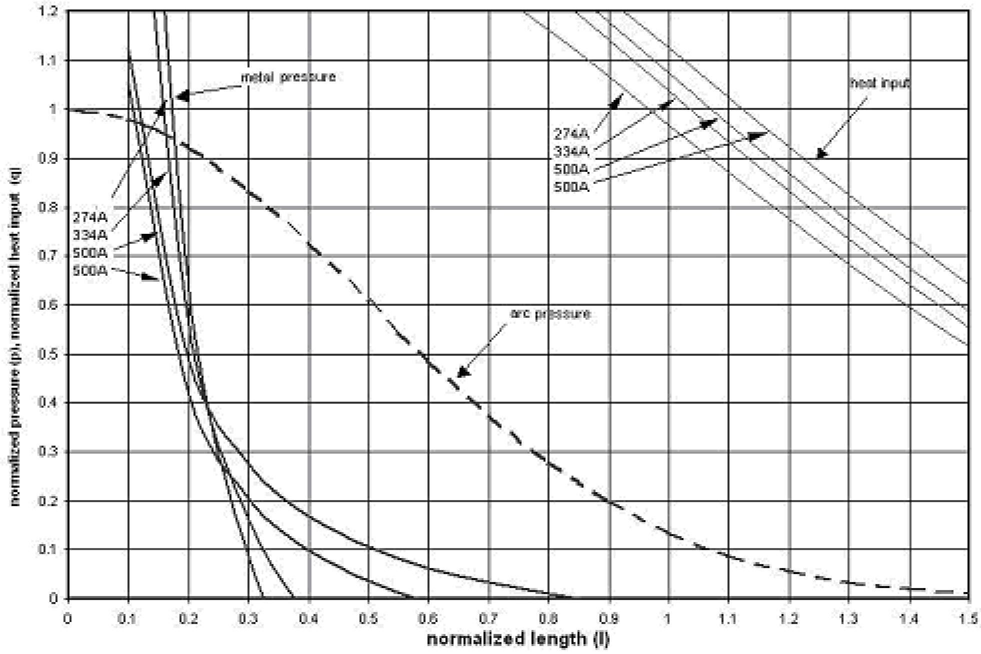


Figure 29 Force balance for open gouging region (Figure 26, for g=0)

7 Conclusions

In this thesis an analysis of the suitability of welding processes for space applications was performed. We concluded that defocused EBW is the best for most EVAs, and GTAW is the best for most IVAs.

An analysis of feasibility of using earth bounded NDT techniques in the space environment was performed. We concluded that x-rays are well suited for EVAs and ultrasound for IVAs. Methods involving liquids are not suitable for EVAs.

A mathematical model was used to analyze the generation of humping in micro-gravity. Space conditions are more prone to humping generation than earth conditions.

The procedure of this thesis could be applied in other cases too, where welding under a "hostile" environment is examined. For instance, the basic principles of the analysis in welding in the space environment could be possibly implemented in underwater welding.

Even though the welding in space is in its primary stages, it will not be long before the need of major repairs arises. Moreover the only way to erect big structures in space that will support habitats for a long period of time is by moving from the mechanical joints, currently used for space structure erection, to welds and together the inevitable need of non destructive inspection as a preventive maintenance.

The most disappointing thing that came out of the research associated with this thesis is the fact that welding in space has been abandoned since 1984 worldwide. There are many different experiments conducted all over the world in different countries. Although the US holds the most publications, the Ukrainians and the Japanese did considerable research on the matter. After the disaster that struck the USA, (Space Shuttle Columbia, February 2003) the future of welding in space becomes even hazier. The fact that there has been a lot written in the press the past few weeks (March 2003) that Russia might stop funding its part of the program for the International Space Station (ISS), makes even the future of the ISS, not to mention welding in space, uncertain. One of the things that might give a boost in welding in space research is the collaboration of scientists all over the world under a common policy instructed and formulated by their government. This might sound too good to be true, as in most of the cases the different countries have completely different policies that prohibit any type of concurrence.

References

1. A. Imakita, M., Miyake,K. Masubuchi, *A Initial Study of Remotely Manipulated Stud Welding for Space Applications.* AWS Journal, April, 1988: p. 25.
2. D.W. Dickinson, H.W.B., et.al., *Welding/Brazing for Space Station Repair*. 1990.
3. Paton, B.E. and V.F. Lapchinski\012D, *Welding in space and related technologies*. 1997, Cambridge, England: Cambridge International Science. 121.
4. Schneider, W.C., et al., *The Skylab results*. 1975, Tarzana, Calif.,: American Astronautical Society. 2 v. (xiv, 1146).
5. Reynerson, C.M., *Design considerations for remotely operated welding in space : task definition and visual weld monitoring experiment*. 1993. p. 245 leaves.
6. Mendez, P.F. *New trends for the manufacturing in the aeronautic industry*. in *New trends in welding in the aeronautic industry*. 2000. San Sebastian, Spain.
7. Goktug, G., *On the effect of environmental pressure on gas tungsten arc welding process*. 1994. p. 76 leaves.
8. Nakamura, T., *A computer-aided system for space welding*. 1994. p. 212 leaves.
9. Cary, H.B., *Modern welding technology*. 4th ed. 1998, Englewood Cliffs, N.J.: Prentice Hall. xii, 787.
10. Cary, H.B. *Variable Polarity Plasma Arc, Keyhole Welding of Aluminum in Welding in Space and the Construction of Space Vehicles by Welding*. 1991. New Carrolton, MD.
11. Berggreen, J. *Economical Manufacturing and Inspection of the Electron-Beam-Welded "Tornado Wing Box",*. in *Advanced Joining of Aerospace Metallic Materials*. 1985. Oberammergau, Germany.
12. Kazakov, V.A.a.O.K., Nazarenko. *State-Of-Art and Prospects of development of Electron Beam Welding of*

Aerospace Vehicles. in *Welding in Space and the Construction of Space Vehicles by Welding*. 1991. New Carrolton, MD: American Welding Society.

13. Boeing, W., http://www.boeing.com. 2000.
14. *Welded Aluminum Aircraft Structures Ready to Take Off*. in *Welding and Metal Fabrication*. 1998.
15. *Welding Technology, Welding Handbook*. 8 ed. Vol. 1. 1987, New York: American Welding Society.
16. Mendez, P.F. and T.W. Eagar, *Welding processes for aeronautics.* Advanced Materials & Processes, 2001. **159**(5): p. 39-43.
17. American Welding Society. Committee on Brazing and Soldering., *Brazing manual*. 3d ed. 1976, Miami: American Welding Society. ix, 309.
18. Dickinson, J.K.W.a.D.W., *The role of welding in space maintenance and repair.* 1988.
19. H.Nishikawa, K., Yoshida, etal, *Characteristics of hollow cathode arc as welding heat source: arc characteristics and melting properties.* Science and Technology of Welding and Joining, 2002. **7**(5).
20. Schultz, *Electron Beam Welding*. 1993: Woodhead Publishing LTD. 232.
21. Mendez, P.F.a.E., T.W. *New Trends in Welding in the Aeronautic Industry*. in *Second Conference on New Trends fro the Manufacturing in the Aeronautic Industry*. 2002. Bilbao, Spain.

22. Chung, T., Kwan, M. et al, *Nondestructive Equipment Study, Final Report, NASA-CR-171865.* TRW Space and Technology Group, NASA L.B. Johnson Space Center, 1985.

23. Lynch, C.T., *On-Orbit Nondestructive Evaluation of Space Platform Structures.* Vitro Technical Journal, 1992. **10**(1): p. 3-16.

24. Ithurralde, G., Simonet, D., *EMATs for on orbit wall remaining thickness measurement after an impact-feasibilty study.* NDT.net, 1999. **4**(1).

25. Finlayson, R.D., Friesel, M., Carlos, M., *Health Monitoring of Aerospace Structures with Acoustic Emission and Acousto-Ultrasonics.* Roma, 15th World Conference on NDT, 2000.

26. Simonet, D., Ithurralde, G., Choffy, J.P., *Non destructive testing in space environment.* Roma, 15th World Conference on NDT, 2000.

27. Georgeson, G.E., Boeing Co. (USA), *Recent advances in aerospace composites NDE.* Proceedings of SPIE, Nondestructive Evaluation and Health Monitoring of Aerospace Materials and Civil Infrastructures, 2002. **4704**(18): p. 104-115.

28. Paton, B.E. and V.F. Lapchinskii, *Welding in space and related technologies*. 1997, Cambridge, England: Cambridge International Science. 121.

29. Halmshaw, R., *Introduction to the Non-Destructive Testing of Welded Joints*. 1988: Edison Welding Institute.

30. Halmshaw, R., *Introduction to the Non-Destructive Testing of Welded Joints*. 1988. p. 74.

31. Russell, C., *International Space Welding Experiment (ISWE),Science Requirements Document*. 1996, NASA-Marshall Space Flight Center.

32. Nishikawa, H., Yoshida, K., Ohji, T. et al, *Fundamental characteristics of GHTA under low pressure.* 1995.

33. Nishikawa, H., Yoshida, K., Maruyama, T. et al, *Gas hollow tungsten arc characteristics under simulated space environment.* Science and Technology of Welding and Joining, 2001. **6**(1).

34. Nishikawa, H., Yoshida, K., Ohji, T. et al, *Characteristics of hollow cathode arc as welding source: arc characteristics and melting properties.* Science and Technology of Welding and Joining, 2002. **7**(5).

35. *ASM Handbook: Welding, Brazing and Soldering*. 1995.

36. P.F. Mendez, T.W., Eagar, *Penetration and deffect formation in high current arc welding.* 2002.

37. K. Nogi, Y., Aoki, et.al., *Behaviour of bubbles in weld undermicro-gravity.* Acta Metallurgica, 1998.

38. Gratzke, U., et al., *Theoretical Approach to the Humping Phenomenon in Welding Processes.* Journal of Physics D: Applied Physics, 1992. **25**: p. 1640-1647.

39. Bradstreet, B.J., *Effect of Surface Tension and Metal Flow on Weld Bead Formation.* Welding Journal, 1968: p. 314s-322s.

40. Schiaffino, S. and A.A. Sonin, *Formation and Stability of Liquid and Molten Beads on a Solid Surface.* Journal of Fluid Mechanics, 1997. **343**: p. 95-110.

41. Yamamoto, T. and W. Shimada. *A Study on Bead Formation in High Speed TIG Arc Welding*. in *International Symposium in Welding*. 1975. Osaka, Japan.

42. Shimada, W. and S. Hoshinouchi, *A Study on Bead Formation by Low Pressure TIG Arc and Prevention of Under-Cut Bead.* Quarterly Journal of the Japan Welding Society, 1982. **51**(3): p. 280-286.

43. Savage, W.F., E.F. Nippes, and K. Agusa, *Effect of Arc Force on Defect Formation in GTA Welding.* Welding Journal, 1979: p. 212s-224s.

44. Tsai, N.-S., *Heat Distribution and Weld Bead Geometry in Arc Welding*, in *Department of Materials Science and Engineering*, T.W. Eagar, Editor. 1983, Massachusetts Institute of Technology: Cambridge, MA. p. 282.

45. Lin, M.L., *Transport Process Affecting the Shape of Arc Welds*, in *Department of Materials Science and Engineering*, T.W. Eagar, Editor. 1985, Massachusetts Institute of Technology: Cambridge, MA. p. 188.

46. Lin, M.L. and T.W. Eagar, *Influence of Arc Pressure on Weld Pool Geometry.* Welding Journal, 1985: p. 163s-169s.

Appendix A

Summary of publications in welding in space (1983-2001)

Year	Country	#	Title
5/6/2000	USA	1	**Category V Compliant Container for Mars Sample Return Missions** , SAE International Congress and **Exposition, Detroit, Michigan** **Author:** Benjamin Dolgin, Joseph Sanok, Donald Sevilla and Laurence J. Bement
12/9/1996	USA	2	**A Portable Surface Contamination Monitor Based on the Principle of Optically Stimulated Electron Emission (OSEE)** 1996 JANNAF Propulsion and Joint Subcommittee Meetings, Albuquerque, New Mexico **Author:** D. F. Perey
5/1/2000	USA	3	**Fatigue Crack Growth Rate Test Results for Al-Li 2195 Parent Metal, Variable Polarity Plasma Arc Welds and Friction Stir Welds , NASA/TM-2000-210098** **Author:** Robert A. Hafley, John A. Wagner and Marcia S. Domack
4/20/1998	USA	4	**Effects of Welding-Induced Initial Geometric Imperfections on the Nonlinear Behavior of the Space Shuttle Superlightweight LO2 Tank** , 39th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and **Materials Conference, Long Beach, California, AIAA 98-1840** **Author:** Michael P. Nemeth, Richard D. Young, Timothy J. Collins and James H. Starnes, Jr.
5/5/1997	USA	5	**Effect of Pressure in Thermoplastic Ribbon Thermal Welding , 42nd International SAMPE Symposium and Exhibition, Anaheim, California** **Author:** J. A. Hinkley, B. C. Messier and J. M. Marchello
8/1/1993	USA	6	**Automated Weld Characterization Using the Thermoelectric Method , Review of Progress in Quantitative Nondestructive Evaluation, Brunswick, Maine** **Author:** J. P. Fulton, M. Namkung and B. Wincheski
4/1/1999	USA	7	**Utilization of Induction Bonding for Automated Fabrication of TIGR**, NASA/TM-1999-209123 **Author:** Jeffrey A. Hinkley, Norman J. Johnston, A. Bruce Hulcher, Joseph M. Marchello and Bernadette C. Messier
5/21/2000	USA	8	**Thermal Edge-Effects Model for Automated Tape Placement of Thermoplastic Composites**, 45th **International SAMPE Symposium and Exhibit, Long Beach, California** **Author:** Robert C. Costen
5/31/1998	USA	9	**Start-on-the-Part Transient Model for In-Situ Automated Tape Placement of Thermoplastic Composites**, **43rd International SAMPE Symposium and Exhibition , Anaheim, California** **Author:** Robert C. Costen and Joseph M. Marchello
5/23/1999	USA	10	**Tape-Drop Transient Model for In Situ Automated Tape Placement of Thermoplastic Composites**, 44th **International SAMPE Symposium and Exhibition , Long Beach, California** **Author:** Robert C. Costen and Joseph M. Marchello
2/1/1986	USA	11	**Implication of welded breccia in Muong Nong-type tektites** **Author:** Futrell, D. S.
12/1/2000	India	12	**Deformation of two welded half-spaces due to inclined shear and tensile point dislocations and a centre of dilation** **Author:** Singh, S. J.; Kumari, G.; Singh, K.; Rani, S.

11/1/1999	India	13	**Displacements and stresses due to a single force in a half-space in welded contact with another half-space** **Author:** Singh, Sarva Jit; Kumari, Gulshan; Singh, Kuldip
8/1/1999	Italy	14	**On tensile cracks close to and across the interface between two welded elastic half-spaces** **Author:**
1/1/1998	USA	15	**Nondestructive Inspection of General Purpose Heat Source (GPHS) Fueled Clad Girth Welds** **Author:** Reimus, M. A. H.; George, T. G.; Lynch, C.; Padilla, M.; Moniz, P.;Guerrero, A.; Moyer, M. W.; Placr, A.
5/1/1994	USA	16	**Effects of non-welded interfaces on guided SH-waves** **Author:** Nihei, Kurt T.; Myer, Larry R.; Cook, Neville G. W.; Yi, Weidong
5/1/1992	USA	17	**Reconstruction and geostatistical analysis of multiscale fracture apertures in a large block of welded tuff** **Author:** Vickers, B. C.; Neuman, S. P.; Sully, M. J.; Evans, D. D.
1/1/1989	USA	18	**The science and practice of welding - Vol.1.: Welding science and technology; Vol.2.: The practice of welding** **Author:** Davies, Arthur C.
1/1/1989	USA	19	**Cold Welding of Aeolian Materials in the Venusian Environment: Experimental and Theoretical Considerations** **Author:** Marshall, J. R.; Fogleman, G.; Greeley, R.
8/1/2000	Canada	20	**Design of a convex and camera mirror support system for Altair, the Gemini-North adaptive optics system** **Author**: Design of a convex and camera mirror support system for Altair, the Gemini-North adaptive optics system
2/1/1999	Italy	21	**The tensile dislocation problem in a layered elastic medium** **Author**: Bonafede, Maurizio; Rivalta, Eleonora
11/1/1998	India	22	**Microimpact phenomena on Australasian microtektites: Implications for ejecta plume characteristics and lunar surface processes** **Author**: Prasad, M. Shyam; Sudhakar,
7/1/1998	USA	23	**New technique for submillimeter-wave reflector construction** **Author:** Martin, Robert N.; Kingsley, Jeffrey S.; Kingsley, Robert K.
11/1/1997	USA	24	**The fate of pyroclasts produced in explosive eruptions on the asteroid 4 Vesta.** **Author:** Wilson, Lionel; Keil, Klaus
3/1/1997	USA	25	**Space weathering of anorthosite from Apollo 16 rock 62255 - SEM studies and microspectrophotometry** **Author:** Wentworth, Susan J.; Keller, Lindsay P.; McKay, David S.
3/1/1997	USA	26	**Some implications of a basal detachment structural model for Olympus Mons** **Author:** McGovern, Patrick J.; Solomon, Sean C.
9/1/1996	China	27	**Real-time measurement of temperature field by colorimetric method** **Author:** Zhang, Hua; Liao, Baojian; Pan, Jiluan
6/1/1994	USA	28	**Cryostat design and construction at the IRTF** **Author:** Toomey, Douglas W.; Stahlberger, Werner E.; Watanabe, Darryl

2/1/1991	USA	29	**Adhesion and abrasion of surface materials in the Venusian aeolian environment** **Author:** Marshall, J. R.; Fogleman, G.; Greeley, R.; Hixon, R.; Tucker, D.
1/1/1990	USA	30	**Electric Probe Measurements in the Boundary Layer of Thermal Arcs: Theory and Experiments.** **Author:** Leveroni-Calvi, Emanuele
8/1/1994	USA	31	**Weldability of a Nickel-Based Superalloy** **Author:** Joseph M. Kalinowski
6/1/1995	USA	32	**A New Cu-8 Cr-4 Nb Alloy for High Temperature Applications** **Author:** D.L. Ellis, G.M. Michal, and R.L. Dreshfield
12/1/1996	USA	33	**Rhenium Mechanical Properties and Joining Technology** **Author:** Brian D. Reed and James A. Biaglow
2/28/1999	USA	34	**Titanium Aluminide Applications in the High Speed Civil Transport** **Author:** Paul A. Bartolotta and David L. Krause
9/1/1995	USA	35	**Evaluation of Rhenium Joining Methods** **Author:** Brian D. Reed and Sybil H. Morren
8/1/1994	USA	36	**Applications of Thin Film Thermocouples for Surface Temperature Measurement** **Author:** Lisa C. Martin and Raymond Holanda
2/1/1993	USA	37	**Development of Thin Film Thermocouples on Ceramic Materials for Advanced Propulsion System Applications** **Author:** Raymond Holanda
6/1/1997	USA	38	**Attachment of Free Filament Thermocouples for Temperature Measurements on CMC** **Author:** Jih-Fen Lei, Michael D. Cuy, and Stephen P. Wnuk
1/1/1983	USA	39	**Metals handbook. Volume 6 - Welding, brazing, and soldering /9th edition** **Author:** Mills, K.
10/1/1996	USA	40	**An Assessment of Molten Metal Detachment Hazards During Electron Beam Welding in the Space Shuttle Bay at LEO fo r the International Space Welding Experiment** **Author:** Fragomeni, James M. (Alabama Univ.)
9/24/1991	USA	41	**Welding in space and the construction of space vehicles by welding; Proceedings of the Conference, New Carrollton,** **Author:** N/A
9/1/1985	USA	42	**Feasibility of remotely manipulated welding in space: A step in the development of novel joining technologies** **Author:** Masubuchi, K. (Massachusetts Inst. of Tech.) Agapakis, J. E. (Massachusetts Inst. Of Tech.) Debiccari, A. (Massachusetts Inst. of Tech.) Vonalt, C. (Massachusetts Inst. Of Tech.)
1/1/1991	Japan	43	**Fusion welding experiments under low-gravity conditions using aircraft** **Author:** Masubuchi, Koichi (MIT) Nayama, Michisuke (Mitsubishi Heavy Industries, Ltd.,Research and Development Center)

2/1/1999	USA	44	**Preliminary Investigation on the Effects of Gravity on Welding Behavior of a 304 Stainless Steel** **Author:** Kang, Nam Hyun (Pennsylvania State Univ.) Howell, Paul R. (Pennsylvania State Univ.) Singh, Jogender (Pennsylvania State Univ.) Lambrakos, Samuel G. (Naval Research Lab.) Marsh, Steven P. (Naval Research Lab.)
9/24/1991	Ukraine	45	**Peculiarities and future development of space welding** **Author:** Shulym, V. F. Lapchinskii, V. F. (Ukrainian Academy of Sciences) Nikitskii, V. P. (NPO Energiia) Demidov, D. L. (Ukrainian Academy of Sciences) Neznamova, L. O. (NPO Energiia)
7/1/1986	USA	46	**High-power laser beam welding in reduced-pressure atmospheres** **Author:** Brown, C. O. Banas, C. M. (United Tehnologies Research Center)
11/1/1986	USA	47	**Factors influencing design and selection of GTAW robotic welding machines for the Space Shuttle main engine** **Author:** Flanigan, L. (Rockwell International Corp.)
1/1/1991	Russia	48	**Welding equipment for space applications** **Author:** Dzhanibekov, V. A. (Centre of Cosmonauts Training) Zagrebel'nyi, A. A. Garvish, S. S. Stesin, V. V. Sheliagin, V. D. (Ukrainian Academy of Sciences) Iurchenko, N. N. (Ukrainian Academy of Sciences) Markov, A. V. (NPO Energiia)
1/1/1991	Ukraine	49	**State-of-art and prospects of development of electron beam welding of aerospace vehicles** **Author:** Kazakov, V. A. (NPO Tekhnomash) Nazarenko, O. K. (Ukrainian Academy of Sciences)
9/24/1991	USA	50	**Laser welding in space** **Author:** Kaukler, W. F. (NASA Lyndon B. Johnson Space Center) Workman, G. L. (Alabama, University)
12/13/1987	USA	51	**Welding in space - An overview** **Author:** Rivett, R. M. (Edison Welding Institute)
1/1/1991	Ukraine	52	**Explosion welding and cutting in aerospace engineering** **Author:** Volgin, L. A. Koroteev, A. IA. Malakovich, A. P. Petushkov, V. G. (Ukrainian Academy of Sciences) Sitalo, V. G. (Special Design Bureau 'Iuzhnaia') Novikov, V. K. (NPO Molniia)
5/1/1998	USA	53	**An Assessment of Molten Metal Detachment Hazards for Electron Beam Welding in the Space Environment: Analysis and Test Results** **Author:** A.C. Nunes, Jr., J.M. Fragomeni*, C. Russell, B. Bhat and J.M. Cramer
3/1/1998	USA	54	**A Case Study of Technology Utilization** **Author:** M. P. Benfield, D. P. Mitchell, M. T. Vanhooser and D. B. Landrum
10/1/1992	USA	55	**Design of a Welded Joint for Robotic, On-Orbit Assembly of Space Structures** **Author:** W.K. Rule and F.P. Thomas
11/1/1999	USA	56	**Low-Pressure Gas Effects on the Potency of an Electron Beam Against Ceramic Cloth** **Author:** A.C. Nunes, Jr., C.K. Russell, F.R. Zimmerman, and J.M. Fragomeni
12/1/1994	USA	57	**Aluminum-Lithium Alloys for Aerospace Applications Workshop George C. Marshall Space Flight Center** **Author:** N/A

3/1/1995	USA	58	**Vaccum Gas Tungsten Arc Welding, phase 1** **Author:** Weeks, J. L.; Krotz, P. D.; Todd, D. T.; Liaw, Y. K.
5/1/1993	USA	59	**Design considerations for remotely operated welding in space: Task definition and visual weld monitoring experiment** **Author:** Reynerson, Charles Martin.
12/1/1992	USA	60	**Shuttle flight experiment preliminary proposal: Demonstration of welding applications in space** **Author:** Brewer, William V.
10/1/1992	USA	61	**A path to in-space welding and to other in-space metal processing technologies using Space Shuttle small payloads** **Author:** Tamir, David
1/1/1984	USA	62	**Refractory alloy technology for space nuclear power applications** **Author:** Cooper, R. H., Jr.; Hoffman, E. E.
8/2/1994	USA	63	**Metal inert gas welding system for use in vacuum** **Author:** Stocks, Charles D. (NASA Marshall Space Flight Center)
1/1/1998	USA	64	**Space Manufacturing: The Next Great Challenge** **Author:** Whitaker, Ann F. (NASA Marshall Space Flight Center) Curreri, Peter (NASA Marshall Space Flight Center) Sharpe, Jonathan B. (Lockheed Martin Corp.) Colberg, Wendell R. (NASA Marshall Space Flight Center) Vickers, John H. (NASA Marshall Space Flight Center)
9/1/1986	USA	65	**Fundamentals and advances in the development of remote welding fabrication systems** **Author:** J.E. Agapakis, K. Masubuchi, C. Von Alt
1/1/1992	USA	66	**Joining experts meet to exchange ideas about welding in space** **Author:** Bob Irving
10/1/1993	USA	67	**U.S. Astronaut experiments with soldering in space** **Author:** Philip Chien
1/1/1994		68	**A computer-aided system for space welding / by Takatoshi Nakamura.** **Author:** Nakamura, Takatoshi.
1/1/1992	USA	69	**The effects of aluminum oxide on inertial welding of aluminum in space applications** **Author:** Smith, Michael Henry
1/1/1991	USA	70	**Management guidelines for the evaluation and selection of the welding technologies for use in outer space / by Ravikumar Ramiah Nagabushanam.** **Author:** Nagabushanam, Ravikumar Ramiah.
1/1/1998	USA	71	**Inertia friction welding of aluminum alloys for space repair applications / by David Edward Guza.** **Author:** Guza, David Edward.
1/1/2000	USA	72	**Application of the NASA risk assessment tool to the evaluation of the Space Shuttle External Tank re-welding process** **Author:** Mulvihill, Robert J; Safie, Fayssal M

11/1/1999	USA	73	**Effects of welding-induced imperfections on behavior of Space Shuttle superlightweight tank** **Author:** Nemeth, Michael P; Young, Richard D; Collins, Timothy J; Starnes, James H, Jr
5/1/1998	USA	74	**Welding safely in space** **Author:** Flinn, Edward D
1/1/1998	USA	75	**Potential for EMU Fabric Damage by Electron Beam and Molten Metal During Space Welding for the International Space Welding Experiment** **Author:** Fragomeni, James M
1/1/1996	Italy	76	**Application of variable polarity plasma arc welding to space modules fabrication** **Author:** Belmondo, A; Ottaviano, S; Fontana, M
1/1/1996	Ukraine	77	**Experience gained at the Paton Electric Welding Institute in the holographic quality control of welded structural components for space applications** **Author:** Paton, B E; Lobanov, L M; Pivtorak, V A
1/1/1996	USA	78	**The Infrastructure of an Integrated Virtual Reality Environment for International Space Welding Experiment** **Author:** Wang, Peter Hor-Ching
1/1/1996	USA	79	**Virtual Reality Simulation of the International Space Welding Experiment** **Author:** Phillips, James A
1/1/1993	USA	80	**Mathematical model of variable polarity plasma arc welding process and fabrication of space system** **Auhtor:** Hung, R J; Long, Y T
1/1/1993	USA	81	**Plasma arc welding repair of space flight hardware** **Author:** HOFFMAN, DAVID S
1/1/1993	USA	82	**Design of an automated system for girth welding general-purpose heat source (GPHS) capsules [space power reactors]** **Author:** Franco-Ferreira, E A; George, T G
1/1/1992	USA	83	**Robotic welding at the Marshall Space Flight Center** **Author:** JONES, CLYDE S
1/1/1992	USA	84	**Weldability of DOP-26 iridium alloy - Effects of welding gas and alloy composition [for space radioisotope thermoelectric generators]** **Author:** Ohriner, Evan K; Goodwin, Gene M; Frederick, D A
1/1/1991	USA	85	**Variable polarity plasma arc welding - The evolution of a state-of-the-art process and its application to Space Station Freedom** **Author:** ANDREWS, THOMAS L
10/1/1990	USA	86	**Welding space vacuum technology** **Author:** JOHNSON, R BARRY
1/1/1990	USA	87	**Characteristics and performance of the variable polarity plasma arc welding process used in the Space Shuttle external tank [Final Report]** **Author:** HUNG, R J; LEE, C C; LIU, J W

1/1/1990	USA	88	**Welding/brazing for Space Station repair** **Author:** DICKINSON, DAVID W; BABEL, H W; CONAWAY, H R; HOOPER, W H
10/26/1989	USA	89	**Laser welding in space [Final Report]** **Author:** WORKMAN, GARY L; KAUKLER, WILLIAM F
8/29/1988	USA	90	**The role of welding in space maintenance and repair** **Author:** WATSON, J K; DICKINSON, D W
8/29/1988	USA	91	**Survey of Soviet space welding technology development** **Author:** WATSON, J K; DICKINSON, D W; ROKHLIN, S I
6/1/1987	USA	92	**Off-line programming motion and process commands for robotic welding of Space Shuttle main engines** **Author:** RUOKANGAS, C C; GUTHMILLER, W A; PIERSON, B L; SLIWINSKI, K E; LEE, J M F
1/1/1985	USA	93	**Remotely manipulated and autonomous robotic welding fabrication in space** **Author:** AGAPAKIS, J E; MASUBUCHI, K
10/1/1985	USA	94	**Unique variable polarity plasma arc welding for space shuttle** **Author:** SCHWINGHAMER, R J
12/1/1999	USA	95	**A hollow electrode GTAW [TIG welding] system developed and tested for space applications** **Author:** MASUBUCHI. K
1/1/1999	USA	96	**Electron beams over the moon [EB welding of space probe components]** **Author:** FARMER, DE
11/1/1998	USA	97	**Welder is up against the wall [wall-mounted robot for welding in a confined space]** **Author:** ASSEMBLY
10/1/1998	Ukraine	98	**Manual electron beam welding thin sheet metal in open space** **Author:** PATON, BE; LAPCHINSKII, VF; MIKHAILOVSKAYA, ES; SHULYM, VF; GAVRISH, SS; GORDAN', GN; NIKITSKII, VP
9/16/1998	Germany	99	**Restricted space - welding with consideration to special hazards** **Author:** SCHMERSE, JP
11/1/1997	Ukraine	100	**Welding in space and related technologies** **Author:** PATON, BE; LAPCHINSKII, VF
4/19/1997	USA	101	**Scientific community of the USA shows interest in welding space technologies** **Author:** PATON WELDING JOURNAL
9/1/1997	Ukraine	102	**Welding in space and in the ocean - technological problems of the 21st century** **Author:** PATON, BE
8/1/1997	Ukraine	103	**Technology of repair of pipelines by electron beam welding and brazing in space conditions** **Author:** ASNIS, EA
11/1/1996	USA	104	**NASA tests space welding procedures underwater** **Author:** ROY, S

11/1/1996	Ukraine	105	**Scientific and technical cooperation between the E.O. Paton Electric Wlding Institute and NASA [National Aeronautics and Space Administration, USA]** **Author:** PATON WELDING JOURNAL
9/1/1996	USA	106	**Welding will play a role in developing a successor to the space shuttle** **Author:** JOHNSEN, MR
3/1/1996	USA	107	**International Space Station - welding will be out of this world** **Author:** WOODWARD, H
2/1/1996	USA	108	**Welding/sealing glass-enclosed space in a vacuum** **Author:** MIDWEST RESEARCH INSTITUTE
12/1/1995	Rusia	109	**Experience with developing equipment for welding with a hollow thermoemission cathode under outer space** conditions **Author:** KAZAKOV, VA; IL'INSKII, AM
4/1/1994	USA	110	**Seam welding the space station Freedom** **Author:** MATERIALS WORLD
9/21/1993	Ukraine	111	**Recent welding processes in the space industry** **Author:** PATON, BE
9/21/1993	Ukraine	112	**Basics of [orbital] joining technology - equipment requirements for welding in space** **Author:** LAPCHINSKII, VF; RIECK, U; SOBISCH, G; KEITEL, S
6/1/1992	USA	113	**Automated robotic variable polarity plasma arc welding (VPPAW) for the space station Freedom project (SSFP)** **Author:** JAFFERY, WS
1/1/1993	USA	114	**Welding in space and low gravity environments** **Author:** ASM INTERNATIONAL; NANCE, M; JONES, JE
1/1/1993	Ukraine	115	**Kinetics of filling the interfibre space with the aluminium melt in welding composites** **Author:** VR; DYKHNO, IS; DEEV, GF; CHERKASOV, EV
6/7/1992	Japan	116	**Laser welding in space** **Author:** KAUKLER, W
5/1/1992	USA	117	**Effects of aluminium oxide on inertial [friction] welding of aluminium in space applications** **Author:** SMITH, MH
12/1/1991	USA	118	**Welding space vacuum technology (Final Report, Oct.1990 - Sept.1991)** **Author:** JOHNSON, RB
9/24/1991	USA	119	**Erection and welding of large-sized structures in space** **Author:** BULATSEV, AR; MOREJNIS, MM; SKOROBOGATOV, SA; MOTRY, VI; SAMILOV, VN; BELETSKII, DV
9/24/1991	USA	120	**Computer aided guidebook on space welding fabrication** **Author:** MASUBUCHI, K; NAKAMURA, T

9/24/1991	USA	121	**CAD [computer aided design] systems for space welded structure design taking into account residual welding stresses and possible defects** **Author:** MAKHNENKO, VI
7/25/1990	Japan	122	**Method of and apparatus for welding panel with space defined therein** **Author:** HONDA GIKEN KOGYO KK
5/1/1990	USA	123	**Welding in space: questions remain** **Author:** KUVIN, BF
5/1/1990	USA	124	**Sensors guide [Space] Shuttle welding** **Author:** GUTOW, D; SMITH, M
5/1/1989	USA	125	**Laser welding in space** **Author:** KAUKLER, WF; WORKMAN, GL; PLASTER, T
3/1/1990	USA	126	**Welding in Space Workshop** **Author:** WORKMAN, GL
9/4/1989	UK	127	**Peculiarities of using welding processes for fabrication and repair of large-sized structures in space** **Author:** PATON, BE; LAPCHINSKII, VF; BULATSEV, AR; BALITSKII, VM; SAMILOV, VN
9/13/1990	Germany	128	**Welding in space** **Author:** PATON, BE
9/18/1990	Germany	129	**Parallel gap and ultrasonic welding at space solar generators - methods, temperature measurement, finite element simulation and low cycle fatigue** **Author:** REUL, S; SNAKKER, W
8/1/1989	USA	130	**Coordinated motion control of multiple robotic devices for welding and redundancy coordination through constrained optimization in Cartesian space** **Author:** AHMAD, S; LUO, SW
8/21/1989	USA	131	**Extravehicular activity [EVA] welding experiment [in space]** **Author:** WATSON, JK
3/28/1989	France	132	**Device for creating a closed space inside two metal pipes which are to be joined by gas-shielded arc welding** **Author:** STEIN INDUSTRIE SA
9/13/1989	Ukraine	133	**Welding in space** **Author:** PATON, BE
4/1/1989	UK	134	**The effects of the space-time distribution of the pulse energy on YAG laser beam welding** **Author:** BADAWI, K; PAINDAVOINE, M; JACROT, G
1/1/1989	Germany	135	**Welding in air and space travel** **Author:** DEUTSCHES INSTITUT FUR NORMUNG; DEUTSCHER VERBAND FUR SCHWEISSTECHNIK
9/1/1988	USA	136	**Potential of a GAS [Get Away Special] can with payload G-169 [TIG welding in space]** **Author:** TAMIR, D
9/1/1988	USA	137	**Robotic and automatic welding development at the [NASA] Marshall Space Flight Center** **Author:** JONES, CS; JACKSON, ME; FLANIGAN, LA

1/1/1987	USA	138	**Welding in space** **Author:** MASUBUCHI, K
6/1/1987	India	139	**TIG welding technology of 7 mm thick 18Ni250 grade maraging steel plates for space applications** **Author:** GHOSH, BR; MURTHY, MSP; SHARMA, SC; MITTAL, MC; NAGARAJAN, KV
9/1/1986	Germany	140	**Process and device for maintaining cleanliness in the interior space of a tube during welding** **Author:** NUKEM GmbH
4/26/1987	USA	141	**Adaptive robotic GTA [TIG] welding for the SSME [space shuttle main engine]: an integrated system** **Author:** SLIWINSKI, KE; RUOKANGAS, CC
1/1/1987	USA	142	**Off-line programming: a robotic space shuttle welding system** **Author:** RUOKANGAS, CC; MARTIN, JF
11/1/1986	Russia	143	**The parameters of the plasma current [flow] in the space within the cathode of a low pressure welding arc** **Author:** NEROVNYI, VM; POD'YAPOL'SKII, GV; YAMPOL'SKII, VM
9/30/1986	France	144	**Investigations on ultrasonic welding for silicon solar cells used for space** **Author:** HOFFMANN, U; SNAKKER, W; SOLL, J
9/30/1986	France	145	**State-of-the-art of solar cell welding technology at ISRO (Indian Space Research Organization): experiences and future plans** **Author:** SRINIVASAMURTHY, N; SUDHAKAR, M; SHARMA, SK; AGRAWAL, BL
9/11/1985	Germany	146	**The welding of aluminium alloys, a new technology in space application** **Author:** MARCHESE, P; BANINO, G
4/1/1986	UK	147	**Diffusion welding of component parts in the aviation and space industries** **Author:** DISAM, J; MIETRACH, D
12/1/1986	Russia	148	**Parameters of the plasma in the internal space within an inconsumable welding arc discharge cathode** **Author:** NEROVNYI, VM; POD'YAPOL'SKII, GV; YAMPOL'SKII, VM
9/16/1985	Germany	149	**The Ariane programme as an example of the application of welding processes in the space industry** **Author:** NAUMANN, WG
9/16/1985	Germany	150	**Welding of the Space Shuttle external tank using the variable polarity plasma process** **Author:** BARHORST, R
6/2/1985	USA	151	**Advanced robotic welding for the Space Shuttle main engine** **Author:** ALLISON, TA; THOMPSON, RF; JONES, CS
6/2/1985	USA	152	**Off-line programming: a robotic space shuttle welding system** **Author:** RUOKANGAS, CC; MARTIN, JF
11/1/1984	USA	153	**Variable polarity plasma arc welding process: its application to the Space Shuttle external tank** **Author:** NUNES, AC; BAYLESS, EO; WILSON, WA
6/1/1983	USA	154	**The variable polarity plasma arc welding process: its application to the Space Shuttle external tank. (First Interim Report)** **Author:** NUNES, AC; BAYLESS, OE; JONES, CS; MUNAFO, PM; BIDDLE, AP; WILSON, WA

6/1/1983	USA	155	**In-house welding studies supporting the prelaunch assessment of the STS-6 [Space Shuttle] main engines** **Author:** HAWKINS, LL
1/1/2000	Japan	156	**Fundamental characteristics of GHTA under low pressure** **Author:** Nishikawa, Hiroshi. Yoshida, Kazuhiro. Ohji, Takayoshi. Suita, Yoshikazu. Tsukuda, Yoshiyuki. Terajima, Noboru. Hatta, Takashi. Kohno, Tettpei. Kawata, Kenji. Inokuma, Rikiya. Masubuchi, Koichi.
1/1/1999	USA	157	**Hollow electrode GTAW system developed and tested for space applications** **Author:** Masubuchi, Koichi
1/1/1999	USA	158	**Hypervelocity impact testing of the pressurized mating adapters for the international space station** **Author:** Dvorak, Bruce D
1/1/1999	Italy	159	**Family of Italian pressurized structures for the International Space Station scenario** **Author:** Boggiatto, D. Sferlazzo, A.
1/1/1993	USA	160	**Using neural networks for seam tracking in welding** **Author:** Akbay, Kunter S. Lawless, Kirby G. Jones, Clyde S.
1/1/1998	USA	161	**Problem of fusion zone re-liquation during repair welding of 2195 aluminum alloy** **Author:** Munafo, Paul M.:
6/1/1998	USA	162	**Welding the Space Shuttle's Al-Li external tank presents a challenge** **Author:** Chien, Philip.
12/1/1997	USA	163	**Behavior of bubbles in welding for repairs in space** **Author:** Nogi, K. Aoki, Y.
1/1/1997	USA	164	**Issues of control of structures using piezoelectric actuators** **Author:** Wang, Q. Liew, Kim M. Wang, D -J.
10/1/1995	USA	165	**Weld joint design for EVA repair of on-orbit fluid systems** **Author:** Jolly, Steven D.
5/1/1995	Japan	166	**Development of arc welding process applied to construction and repair of space vehicles and structures in space** **Author:** Suita, Yoshikazu. Masubuchi, Koichi. Tukuda, Yoshiyuki. Terajima, Noboru. Ogasawara, Masanobu. Takahashi, Hisashi.
7/7/1995	USA	167	**Switch to Al-Li lightens shuttle fuel tank** **Author:** Kuvin, Brad F
8/3/1993	Japan	168	**Study on gas tungsten arc welding in space (1st report)** **Author:** Suita, Yoshikazu. Tukuda, Yoshiyuki. Takagi, Takashi. Ohji, Takayoshi. Masubuchi, Koichi.
1/1/1993	USA	169	**Space applications industrial laser system** **Author:** Mueller, Robert. Bible, Brice. McCay, Mary Helen. Sharp, Michael. McCay, Dwayne.
8/14/1993	USA	170	**Space charge in plasma arc welding and cutting** **Author:** Dowden, John. Kapadia, Phiroze. Fenn, Bob.
6/1/1993	USA	171	**Microstructural changes during laser welding of stainless steel under reduced gravity Environment** **Author:** Wang, G. Tandon, K N.

1/1/1993	USA	172	**In-space welding - visions & realities** **Author:** Tamir, David. Siewert, Thomas A. Masubuchi, Koichi. Flanigan, Lee. Su, Renjeng. Eagar,Thomas W.
1/1/1992	USA	173	**Robotic assembly of welded truss structures in space.** **Author:** Jones, Clyde S. Thomas, Frank. Brewer, William V.
1/1/1992	USA	174	**On-orbit chipless cutting and tube welding in Space Station Freedom.** **Author:** Wessels, William R. Mulder, Mitchell D. Daniel, Brace B.
1/1/1991	USA	175	**Variable polarity plasma arc welding the evolution of a state-of-the-art process and its application to space station Freedom.** **Author:** Andrews, Thomas L
9/1/1991	USA	176	**EB welding of launch vehicles.** **Author:** Szabo, Attiia
3/1/1990	Ukraine	177	**Technological aspects of welding in space.** **Author:** Paton, Boris E
Unknown	USA	178	**Manufacturing implementation of off-line programming for the space shuttle main engines.** **Author:** Sliwinski, K E. Anderson, R R. Pierson, B L. Guthmiller, W A.
1/1/1988	USA	179	**Welding the space station common module prototype.** **Author:** Bosworth, T J. Miller, C M. Griffee, C C.
1/1/1988	USA	180	**Remotely Manipulated Stud Welding For Space Applications.** **Author:** Masubuchi, K. Imakita, A. Hara, K. Miyake, M
1/1/1988	USA	181	**Welding Of The Space Station Common Module Prototype.** **Author:** Bosworth, T J. Griffee, C C. Miller, C M. Wilson, W A.
1/1/1988	USA	182	**Space Commercialization: An Overview By An Aerospace Corporation.** **Author:** Viola, J T
1/1/1987	USA	183	**Better Welds For Launch Vehicles.** **Author:** Schwinghamer, Robert J
3/1/1987	USA	184	**Development Of A CCTV System For Welder Training And Monitoring Of Space Shuttle Main Engine Welds.** **Author:** Gordon, S S. Flanigan, L A. Dyer, G E.
8/19/1985	USA	185	**EB Welding Minimizes Small Part Distortion.** **Author:** Bak, David J
10/5/1986	USA	186	**Welding The Space Shuttle Engine.** **Author:** Arnold, Greg. Jones, Clyde.
10/10/1983	USA	187	**Special Tooling, Fixtures Weld Tubing.** **Author:** Tryon, Jerry. Contreras, Jay.
9/9/1984	USA	188	**Variable Polarity Plasma Arc Welding On The Space Shuttle External Tank.** **Author:** Nunes, A C Jr. Bayless, E O Jr. Jones, C S III. Munafo, P M. Biddle, A P. Wilson, W A.

1/1/1983	USA	189	**Nasa's Use Of Robotics In Building The Space Shuttle.** **Author:** Fernandez, K. Jones, C S. Roberts, M L.
8/8/1983	USA	190	**Simple Tooling Positions Tube Welds.** **Author:** Tryon, Jerry. Contreras, Jay.
11/1/1996	USA	191	**Assessment of Corona/Arcing Hazard for Electron Beam Welding in Space Shuttle Bay at LEO for ISWE: Test Results.** **Author:** Nunes AC; Russell C; Vaughn J; Stocks C; ODell D.
11/1/1993	USA	192	**Marshall Automated Weld System (MAWS).** **Author:** Russell Ck; Lawless Kg; Nunes Ac.
4/1/1993	USA	193	**Welding In Space: Procedures And Equipment. (A Bibliography From The Weldasearch Database).** **Author:** Nerac, Inc., Tolland, Ct. National Technical Information Service
12/1/1992	USA	194	**Shuttle Flight Experiment Preliminary Proposal: Demonstration Of Welding Applications In Space.** **Author:** Brewer Wv
6/1/1991	USA	195	**Vacuum Vapor Deposition: A Spinoff Of Space Welding Development.** **Author:** Poorman Rm
3/1/1991	USA	196	**Robotics In Space-Age Manufacturing.** **Author:** JONES C
5/1/1989	USA	197	**Hierarchical Architecture For Automated Electrom Beam (Eb) Welding Systems: Exception Handling And Robust Controllers.** **Author:** Greer Jt
6/1/1988	USA	198	**In-Space Technology Experiments Program: Instep.** **Author:** Ambrus Jh
6/1/1983	USA	199	**Variable Polarity Plasma Arc Welding Process: Its Application To The Space Shuttle External Tank.** **Author:** Nunes Ac Jr; Bayless Oe Jr; Jones Cs Iii; Munafo Ap; Wilson Wa.
4/19/1997	USA	200	**There's a hole in my spacecraft (welding in space).** **Author:** Chien, Philip
4/1/1994	USA	201	**Welded joints for robotic, on-orbit assembly of space structures.** **Author:** Rule, William K. Thomas, Frank P.
4/1/1992	USA	202	**Welding for space.** **Author:** Kuvin, Brad F
1/1/1992	USA	203	**Joining metals in hostile environments.** **Author:** Hunt, Margaret
7/1/1991	USA	204	**Electron beam welding, Soviet style: a front runner for space.** **Author:** Irving, Bob
6/1/1990	USA	205	**Plasma arc welding under normal and zero gravity.** **Author:** Keanini, R. G. Rubinsky, B.

5/1/1990	USA	206	**Welding in Space** **Author:** Workshop, Huntsville, Ala. Nov. 8-9, 1989
1/1/1993	Canada	207	**Laser Beam Welding Of Aisi 316 Stainless Steel In Microgravity Environment: Experiments Aboard A KC-135 Flight** **Author:** Wang, Guoqing
1/1/1991	USA	208	**Erection and welding of large-sized structures in space** **Author:** Bulattsev, A. R. Moreinis, M. M. Skorobogatov, S. A. Motry, V. I. Samilov, V. N. Beletskii, D. V. (Ukrainian Academy of Sciences)
1/1/2001	Japan	209	**Gas hollow tungsten are characteristics under simulated space environment** **Author:** Nishikawa H, Yoshida K, Maruyama T, Ohji T, Suita Y, Masubuchi K
8/1/1994	Japan	210	**Examples Of Aluminum Use In Japan - Special Treatments Of Aluminum For Ultrahigh-Vacuum Applications** **Author:** Ishimaru H
10/1/1992	China	211	**Microcomputer-Based Welder Training Simulator** **Author:** Wu Cs
8/8/1991	USA	212	**Welding Role In Space Exploration** **Author:** Dickinson Dw
7/7/1991	USA	213	**Electron-Beam Welding, Soviet Style - A Front Runner For Space** **Author:** Irving B
3/1/1990	USA	214	**Workshop Launches Welding In Space Research** **Author:** Newtonmontiel B
1/1/1983	USA	215	**Welding Iridium Heat-Source Capsules For Space Missions** **Author:** Kanne Wr
1/1/1987	USA	216	**Parallel Link Manipulator--Invention Patent.** **Author:** Landsberger-Se; Sheridan-Tb
1/1/1986	Ukraine	217	**Problems of space technology of metals** **Author:** A.D. Grishkevich, P.L. Babenko, et al.
1/1/1985	Ukraine	218	**Problems of space technology of metals** **Author:** Yu.I. Drabovich , N.N. Yurchenko, et al.
1/1/1986	Ukraine	219	**Analysis of permanent joints in tubular elements of the welding-brazing and brazing type produced using the versatile tool** **Author:** A.A. Zagrebel'nyi, S.S. Gavrysh, A.R. Bulatsev, et al.
1/1/1994	Ukraine	220	**Twenty-five years since the first welding experiment in space** **Author:** V.N. Kubasov, V.P. Nikitskii, V.F. Lapchinskii
1/1/1984	Ukraine	221	**Some problems of welding thin sheet metal in space** **Author:** V.F. Lapchinskii

1/1/1985	Ukraine	222	**Tests of a hand electron beam tool in free space** **Author:** V.F. Lapchinskii, V.P. Nikitskii
1/1/1989	Japan	223	**Space technologies of joining developed in the USA** **Author:** K. Masubuchi
1/1/1995	Ukraine	224	**A high power small electron beam equipment for technological operations and physical experiments under space condtions.** **Author:** B.E. Paton, D.A. Dudko and V.F. Lapchniskii
1/1/1985	Ukraine	225	**An Investigation Of The Properties And Structure Of Electron Beam Welled Joints In 1210 Alloy, Produced Under Different Gravitation Conditions At Low Temperatures.** **Author:** D.M. Rabkin and V.F. Lapchiniskii
1/1/1989	Japan	226	**Space Stations and Colonies** **Author:** E. Suedzawa
1/1/1986	Ukraine	227	**Effect of Gravitation Forces, Dissolved Hydrogen and Initial Temperature on the Properties and Density of Joints in Electron Beam Welding of Light Structural Alloys.** **Author:** E.G. Ternovoi, et. al.
1/1/1991	USA	228	**Telerobotik Fluid Line Repair Tool Development, Welding in Space and the Construction of Space Vehicles** **Author:** R.N. Anderson
1/1/1991	USA	229	**Prediction of Structural Materials Performance at Long-Term Service in Space Conditions** **Author:** S.V. Bakushin, Y.U. Morozov, V.F. Lapchiniskii, D.L. Demidov
1/1/1989	Helsinki	230	**The Test of the Versatile Hand Electron Beam Tool in Space. Wedding Under Extreme Condtions** **Author:** B. E. Paton, V.Z. Dzhanibekov, et al.
1/1/1990	Canada	231	**Materials Science Study of Specimens of Permanent Joints and Coatings Made in Space.** **Author:** B.E. Paton, V.F. Lapchinskii
1/1/1991	USA	232	**State of Art and Prospects of Development of Aerospace Engineering in the USSR** **Author:** B.E. Paton
6/25/2001	Japan	233	**Welding of Stainless Steel by Space GHTA Welding Using a Compact Wire Feeder in a Vacuum (in Japanese)** **Author:** Suita, Yoshikazu. Yamaji, Naoki. Terajima, Noboru. Tsukuda, Yoshiyuki. Hara, Takuo. Ohji,Takayoshi. Masubuchi, Koichi. Transactions of the Japan Society of Mechanical Engineers C, Vol.67, No.658(2001), pp.2044-2050
5/5/2001	Japan	234	**GHTA Spot Welding Experiments of Aluminum and Titanium Plates under Simulated Space Environment (in Japanese)** **Author:** Suita, Yoshikazu. Kurokawa, Teppei. Sato, Junko. Shobako, Shinichiro. Kohno, Teppei. Tsukuda, Yoshiyuki. Terajima, Noboru. Masubuchi, Koichi. Journal of the Japan Society for aeronautical and Space Sciences, Vol.49, No.568(2001), pp.155-161

3/1 /2001 Japan **Gas hollow tungsten arc characteristics under simulated space environment**
Author: Nishikawa, H. Yoshida, K. Maruyama, T. Ohji, T. Suita, Y. Masubuchi, K.
235 Science and Technology of Welding and Joining, Vol.6, No.1(2001), pp.12-16

2/1/2001 Japan **Gas hollow tungsten arc welding experiments in aircraft-borne simulated space environment**
Author: Suita, Y. Tsukuda, Y. Terajima, N. Hatta, T. Kono, T. Inokuma, R. Kawada, K. Oji, T. Nishikawa, H. Yoshida, K. Masubuchi, K.
236 Welding International, Vol.15, No.2(2001), pp.100-107

2/1 /2001 Japan **Fundamental characteristics of gas hollow tungsten arc at low pressure**
Author: Nishikawa, H. Yoshida, K. Oji, T. Suita, Y. Tsukuda, Y. Terajima, N. Hatta, T. Kono, T. Kawata, K. Inokuma, R.
237 Welding International, Vol.15, No.2(2001), pp108-114

1/16/2001 Japan **Welding Experiments by High Power Diode Laser under Ultra High Vacuum Conditions in Space Station Orbit (in Japanese)**
Author: Suita, Y. Kurokawa, T. Sato, J. Shobako, S. Nagai, H, Tabakodani, E. Terajima, N. Tsukuda, Y. Fujisawa, S. Ohji, T. Fujisawa, S. Ohji, T. Masubuchi, K. Fujishima S, Masubuchi, K. Fujishima S.
238 Proc. of The Seventeenth Space Utilization Symposium, Vol.17(2001), pp.339-342

1/16/2001 Japan **GHTA Welding Experiments under Ultra High Vacuum Condition in Space Station Orbit (in Japanese)**
Author: Suita, Y. Sato, J. Shobako, S. Kurokawa, T. Takai, D. Terajima, N. Tsukuda, Y.
239 Proc. of The Seventeenth Space Utilization Symposium, Vol.17(2001), pp.335-338

7/14/2000 Japan **Gas Hollow Tungsten Arc Characteristics under Simulated Space Environment**
Author: Nishikawa, Hiroshi. Yoshida, Kazuhiro. Maruyama, Toshikazu. Ohji, Takayoshi. Suita, Yoshikazu. Masubuchi, Koichi.
240 International Institute of Welding, 53rd Annual Assembly, Doc.212-968-00, Florence, Italy

5/5/2000 Japan **GHTA Welding Experiments under Simulated Space Environment in Flying Laboratory (in Japanese)**
Author: Suita, Yoshikazu. Tsukuda, Yoshiyuki. Terajima, Noboru. Hatta, Takashi. Kono, Teppei. Inokuma, Rikiya. Kawada, Kenji. Ohji, Takayoshi. Nishikawa, Hiroshi. Yoshida, Kazuhiro. Masubuchi, Koichi.
241 Quarterly Journal of the Japan Welding Society, Vol.18, No.2(2000), pp228-235

5/5/2000 Japan **Fundamental Characteristics of GHTA under Low Pressure (in Japanese)**
Author: Nishikawa, Hiroshi. Yoshida, Kazuhiro. Ohji, Takayoshi. Suita, Yoshikazu Tsukuda, Yoshiyuki. Terajima, Noboru. Hatta, Takashi. Kohno, Teppei. Kawata, Kenji. Inokuma, Rikiya. Masubuchi, Koichi.
242 Quarterly Journal of the Japan Welding Society, Vol.18, No.2(2000), pp272-279

1/10/2000 Japan **GHTA Welding Experiments under Simulated Space Environment by Parabolic Flight (in Japanese)**
Author: Suita, Yoshikazu. Tsukuda, Yoshiyuki. Terajima, Noboru. Hatta, Takashi. Kono, Teppei. Inokuma, Rikiya. Kawada, Kenji. Ohji, Takayoshi. Nishikawa, Hiroshi. Yoshida, Kazuhiro. Masubuchi, Koichi.
243 Proc. of The Sixteenth Space Utilization Symposium, Vol.16(2000), pp.257-260

12/1 /1998	Japan	244	**Behavior of Bubbles in Weld Under Microgravity** **Author:** Nogi, K. Aoki, Y. Fujii, H. Nakata, K Acta Materialia, Vol.46, No.12(1998), pp.4405-4413
6/25/1998	Japan	245	**Welding of SUS304 Stainless Steel by Space GHTA Welding (in Japanese)** **Author:** Suita, Yoshikazu. Masubuchi, Koichi. Terajima, Noboru. Tsukuda, Yoshiyuki. Transactions of the Japan Society of Mechanical Engineers C, Vol.64, No.622(1998), pp.2304-2309
2/1 /1998	Japan	246	**Weld Formation in Microgravity** **Author:** Nogi, Kiyoshi. Aoki, Yasuhiro. Fujii, Hidetoshi. Nakata, Kazuhiro. Kaihara, Shoichiro. ISIJ(The Iron and Steel Institute of Japan) International, Vol.38, No.2(1998), pp.163-170
11/1 /1997	Japan	247	**Welding aluminium alloy by hollow electrode TIG in a vacuum** **Author:** Suita, Y. Tsukuda, Y. Terajima, N. Takahashi, H. Ogasawara, M. Ohji, Takayoshi. Masubuchi, Koichi. Welding International, Vol.11, No.8(1997), pp605-614
6/1/1997	Japan	248	**Behavior of bubbles in welding for repairs in space** **Author:** Nogi, K. Aoki, Y.
11/5/1996	Japan	249	**Welding of Aluminum alloy by Gas Hollow Tungsten Arc Welding Method in a Vacuum (in Japanese)** **Author:** Suita, Yoshikazu. Tsukuda, Yoshiyuki. Terajima, Noboru. Takahashi, Hisashi. Ogasawara, Masanobu. Ohji, Takayoshi. Masubuchi, Koichi. Quarterly Journal of the Japan Welding Society, Vol.14, No.4(1996), pp.633-640
1/1/1996	Japan	250	**Observation Of Welding Phenomena In Microgravity Environment** **Author:** Nogi, Kiyoshi. Aoki, Yasuhiro. Nakata, Kazuhiro. Maeda, Masakazu. Kaihara, Shoichiro. Kamai, Masayoshi. Makino, Yukio. Proc. of JIMIS-8(1996), pp.257-260
5/25/1995	Japan	251	**Development of Arc Welding Process Applied to Construction and Repair of Space Vehicles and Structures in Space (in Japanese)** **Author:** Suita, Yeshikazu, Masubuchi, Koichi. Tsukuda, Yoshiyuki. Terajima, Noboru. Ogasawara, Masanobu. Takahashi, Hisashi. Transactions of the Japan Society of Mechanical Engineers C, Vol.61, No.585(1995), pp.2134-2140
3/20/1995	Japan	252	**Challenge Space: Development of Space Welding Process (in Japanese)** **Author:** Suita, Yoshikazu. Journal of High Temperature Society, Vol.21, No.2(1995), pp.33-42
11/10/1994	Japan	253	**Development of Gas Hollow Tungsten Arc Welding Process for Construction and Repair of Space Vehicles and Structure in Space (in Japanese)** **Author:** Suita, Yoshikazu. Ohji, Takayoshi. Tsukuda, Yoshiyuki. Terajima, Noboru. Masubuchi, Koichi. Proc. of The Sixteenth Space Utilization Symposium, Vol.11(1994), pp.246-249

4/14/1994	Japan	254	**Study on welding phenomena under micro-gravity (Oral presentation in Japanese)** **Author:** Nezaki, Koji. Kaihara, Shoichiro. Kuribayashi, Munetake. Tanji, Akira. Kawachi, Keisuke. Preprints of the National Meeting of Japan Welding Society, No.54(1994), pp.210-211
4/1 /1994	Japan	255	**Study of gas tungsten arc welding in space (1st Report)** **Author:** Suita, Yoshikazu. Tsukuda, Yoshiyuki. Takagi, Takashi. Ohji, Takayoshi. Masubuchi, Koichi. Welding International, Vol.8, No.4(1994), pp.269-273
8/5/1993	Japan	256	**A Study on Gas Tungsten Arc Welding in Space (in Japanese)** **Author:** Suita, Yoshikazu. Tsukuda, Yoshiyuki. Takagi, Takashi. Ohji, Takayoshi. Masubuchi, Koichi. Quarterly Journal of the Japan Welding Society, Vol.11, No.8(1993), pp.423-427
4/10/1991	Japan	257	**Aircraft Experiment of the Fusion Welding under Low-Gravity (Oral presentation in Japanese)** **Author:** Nayama, Michisuke. Imada, Takehiko. Preprints of the National Meeting of Japan Welding Society, No.48(1991), pp.156-157
9/5/1990	USA	258	**Welding in Space (in Japanese)** **Author**: Masubuchi, Koichi. Journal of the Japan Welding Society, Vol.59, No.6(1990), pp.421-427
1/1/1989	USA	259	**An overview of joining technologies related to space explorations in the United States (in Japanese)** **Author:** Masubuchi, Koichi. Joining Assembling Engineering, Vol.5, No.8(1989), pp.103-108
5/1/1988	Japan	260	**Welding in Space (in Japanese)** **Author:** Imakita, Akihiko Bulletin of the Society of Naval Architects of Japan, No.707(1988), pp.277-282

Appendix B

Analytical calculations of Chapter 6

Figure 24 Data

Inputs

s (ppm)	ρ (kg/m^3)	σ (N/m)	θ (degrees)	α_e (degrees)	ΔH_m (J/kg)	g (m/s^2)
400	7000	1.15	90	90	265000	9.81

		pi =	3.141592654	= 180°	
r_1 =	1	pi/2 =	1.570796327	= 90°	θ
r_2 =	0.4	pi/4 =	0.785398163	= 45°	θ/2

Inputs / **Results**

I (A)	V (mm/s)	L_a (mm)	H (mm)	D (mm)	P_{max} (kPa)	P_{max} (N/m^2)	σ_P (mm)	Q_{max} (W/mm2)	σ_Q (mm)	Q_{solid} (W/mm^2)	l_{eq}	q_{eq}	L_i
300	9.58	4.1	3.4	1.716	1.156	1156	1.883	68.55	2.913	40.341	1.041199554	0.41	7.5
350	8.39	4.4	3.9	1.958	1.401	1401	1.969	72.83	3.104	43.183	0.972815252	0.47	7.9
400	7.76	4.7	4.2	2.316	1.654	1654	2.046	76.47	3.284	45.380	0.986021358	0.47	8.2
450	6.36	5.2	5	2.775	1.915	1915	2.117	77.24	3.500	46.062	0.935221445	0.525	8.5
500	4.61	6.2	6.6	3.783	2.183	2183	2.182	72.98	3.808	43.611	0.859183789	0.63	8.7
						1662							

Data for plotting of the pressure arc gaussian distribution.

l	p_a
0	1
0.1	0.980198673
0.2	0.923116346
0.3	0.835270211
0.4	0.726149037
0.5	0.60653066
0.6	0.486752256
0.7	0.375311099
0.8	0.2780373
0.9	0.197898699
1	0.135335283
1.1	0.088921617
1.2	0.056134763

qa

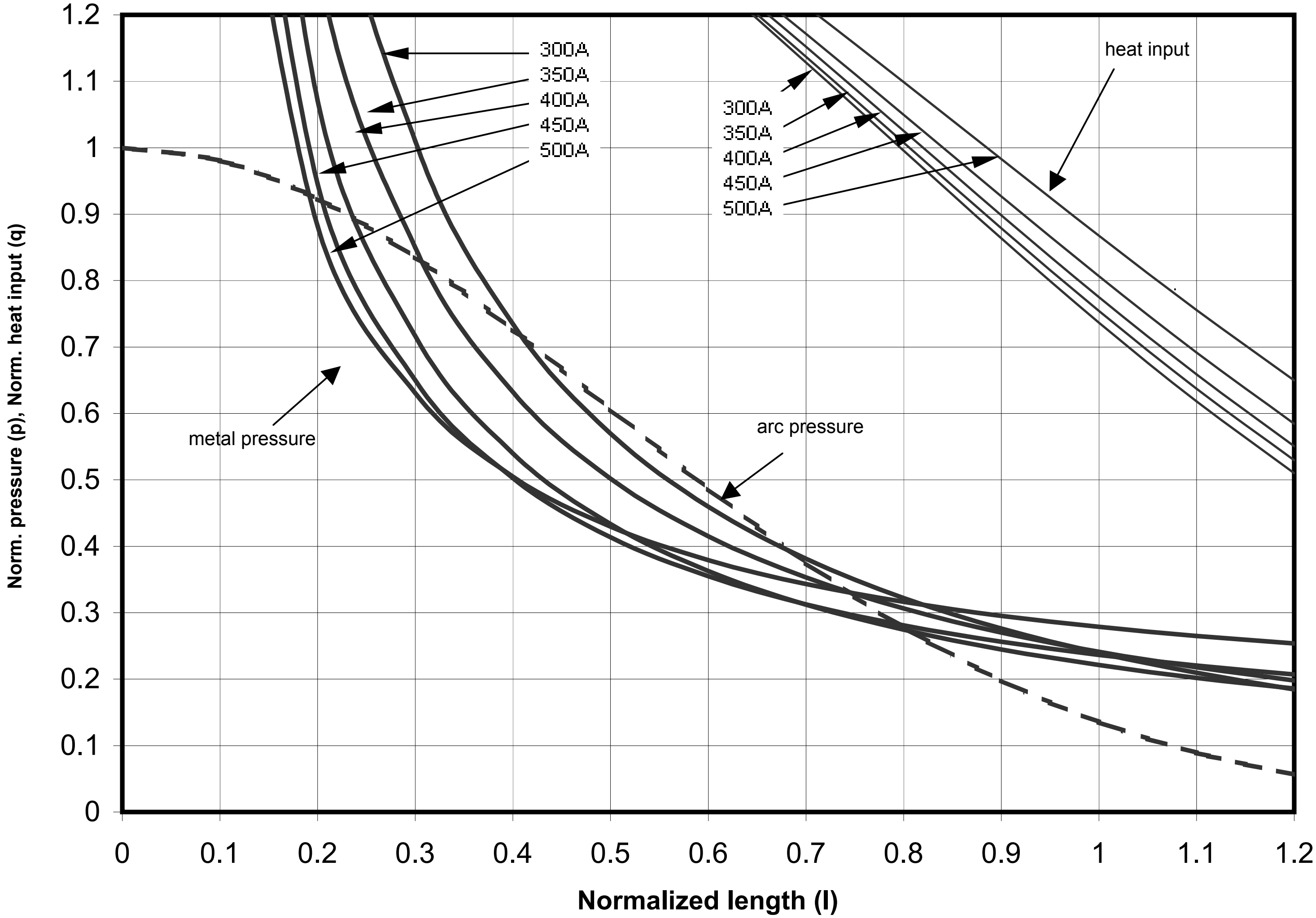
300A	350A	400A	450A	500A
1.699308438	1.686480184	1.685016108	1.676788327	1.673482987
1.685167078	1.672963797	1.671984545	1.664562679	1.662524887
1.643445181	1.633061135	1.633491445	1.62841797	1.630079239
1.576191507	1.568660439	1.571295526	1.569912478	1.57740417
1.48663464	1.482743554	1.488179395	1.491519097	1.506506329
1.37892618	1.37915712	1.387743187	1.396452017	1.420014057
1.257822302	1.262327511	1.27414638	1.288448425	1.321015867
1.128337621	1.136948908	1.151823538	1.171525867	1.212878038
0.995406221	1.007674923	1.025200897	1.049737103	1.099056293
0.863581116	0.878841493	0.898438615	0.926943012	0.982916103
0.736796285	0.754242943	0.775218709	0.806620666	0.867574283
0.618206009	0.63697525	0.658592051	0.691718635	0.755771651
0.510106105	0.529351882	0.550890304	0.584565835	0.649782832

		Normalized length (l)											
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2
p_a	300 A	3.211	1.560	1.010	0.735	0.570	0.460	0.381	0.322	0.276	0.240	0.210	0.185
	350 A	2.588	1.284	0.850	0.632	0.502	0.415	0.353	0.307	0.270	0.241	0.218	0.198
	400 A	2.133	1.071	0.717	0.540	0.434	0.363	0.312	0.274	0.245	0.221	0.202	0.186
	450 A	1.833	0.946	0.650	0.503	0.414	0.355	0.313	0.281	0.256	0.237	0.220	0.207
	500 A	1.637	0.882	0.631	0.505	0.430	0.379	0.343	0.316	0.295	0.279	0.265	0.254

Use of solver to determine the values of l_{eq}.

Target, Solution	1.041199554	0.972815252	0.986021358	0.935221445	0.859183789
Eqn = 0	0.112	0.098	0.081	0.075	0.075
	300 A	350 A	400 A	450 A	500 A

Figure 24



300A
350A
400A
450A
500A
300A
350A
400A
450A
500A
heat input
metal pressure
arc pressure
Norm. pressure (p), Norm. heat input (q)
Normalized length (l)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2

Figure 25 Data

Table 4

s (ppm)	ρ (kg/m^3)	σ (N/m)	θ (degrees)	α_e (degrees)	ΔH_m (J/kg)	g (m/s^2)
6	6900	1.82	30	60	265000	9.81

pi = 3.141593 = 180°

r_1 =	1	pi/6 =	0.523599 = 30°	θ
r_2 =	0.4	pi/12 =	0.261799 = 15°	θ/2

Table 5 **Results**

I (A)	V (mm/s)	L_a (mm)	H (mm)	D (mm)	P_{max} (kPa)	P_{max} (N/m^2)	σ_P (mm)	Q_{max} (W/mm2)	σ_Q (mm)	Q_{solid} (W/mm^2)	l_{eq}	q_{eq}	L_i
274	11.6	7.3	0.9	0.0917	1.4202	1400	1.721	41	3.4	25.64	1.41		6.9
334	14.1	7.5	1.1	1.1250	1.8169	1800	1.822	47	3.6	27.27	1.30	0.43	7.3
500	10.6	9.4	3.0	3.0000	3.0013	3000	2.048	53	4.4	29.88	1.04	0.62	8.2
500	15.0	8.5	2.2	2.1670	3.0013	3000	2.048	57	4.2	32.37	1.12	0.56	8.2
						2300							

Data for plotting of the pressure arc gaussian distribution.

l	p_a
0	1
0.1	0.980198673
0.2	0.923116346
0.3	0.835270211
0.4	0.726149037
0.5	0.60653066
0.6	0.486752256
0.7	0.375311099
0.8	0.2780373
0.9	0.197898699
1	0.135335283
1.1	0.088921617
1.2	0.056134763
1.3	0.034047455
1.4	0.019841095
1.5	0.011108997

qa

274A	***334A***	***500A***	***500A***
1.604610298	1.712388	1.774094	1.769594
1.59651961	1.703819	1.766259	1.761257
1.572491492	1.678368	1.74296	1.736483
1.533245561	1.636793	1.70481	1.695964
1.479941308	1.580312	1.652799	1.640822
1.414121201	1.510547	1.588252	1.57255
1.337636587	1.429448	1.512774	1.492953
1.252561357	1.339199	1.428185	1.404062
1.161098982	1.242123	1.336442	1.308052
1.065488689	1.140582	1.23957	1.207152
0.96791631	1.036885	1.139587	1.103564
0.870434582	0.933207	1.038435	0.999382
0.774896734	0.83151	0.937922	0.896528
0.682905938	0.733499	0.839672	0.7967
0.595781909	0.640581	0.745088	0.701333
0.514544689	0.553849	0.655332	0.611579

Calculation of the normalized pressure for each different case.

		Normalized length (l)														
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5
p_a	***274A***	2.211	1.030	0.637	0.440	0.322	0.243	0.187	0.145	0.112	0.086	0.065	0.047	0.032	0.019	0.007
	334A	1.652	0.785	0.496	0.352	0.265	0.207	0.166	0.135	0.111	0.092	0.076	0.063	0.052	0.042	0.034
	500A	0.966	0.503	0.349	0.272	0.226	0.195	0.173	0.156	0.143	0.133	0.125	0.118	0.112	0.107	0.102
	500A .	0.938	0.476	0.321	0.244	0.198	0.167	0.145	0.128	0.116	0.105	0.097	0.090	0.084	0.079	0.074

Use of solver to determine the values of l_{eq}.

	274A	***334A***	***500A***	***500A .***
Target, Solution	1.416470415	1.301441233	1.044502189	1.117053533
Eqn = 0	-0.001	0.018	0.016	0.013

Figure 25

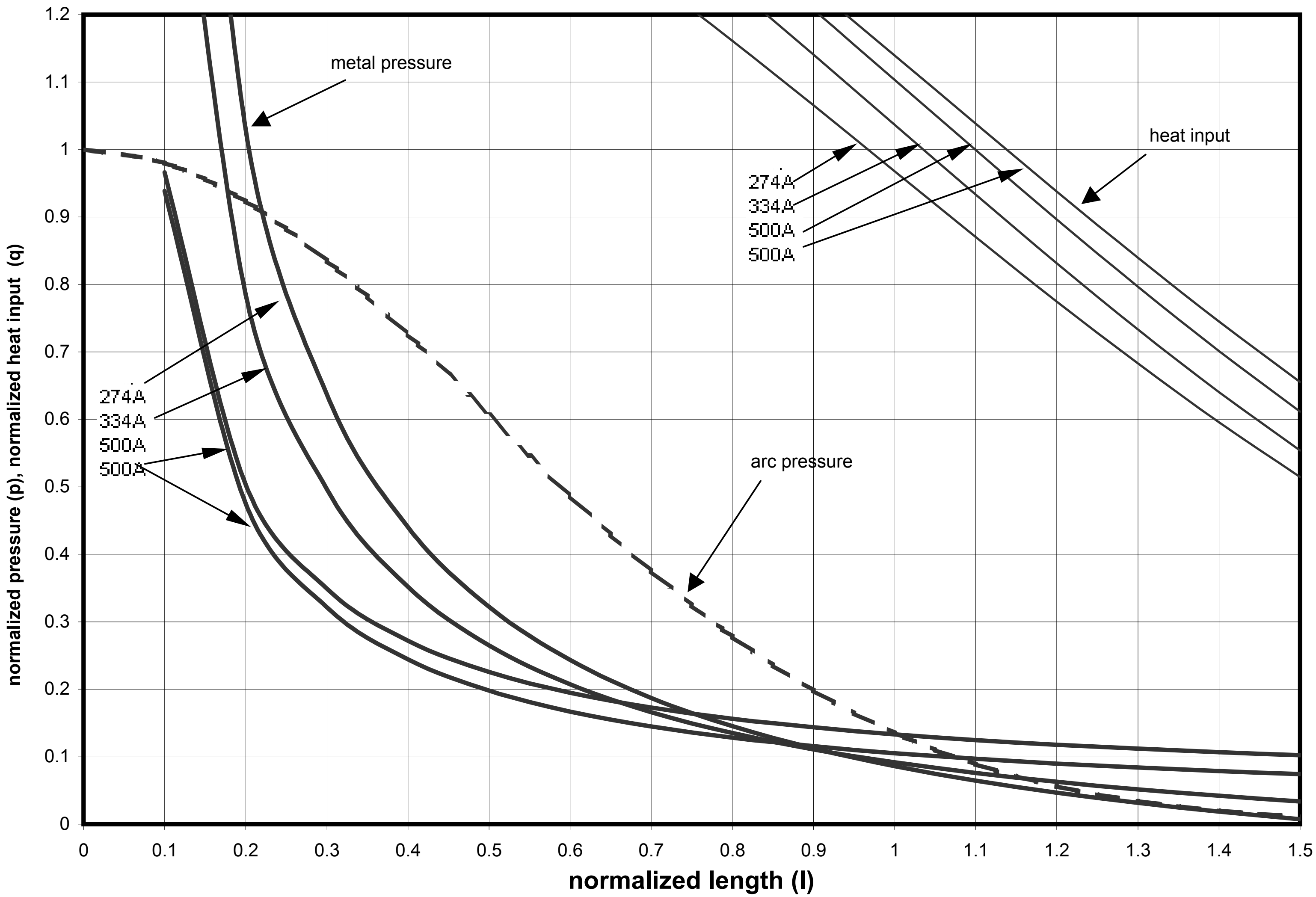

metal pressure
heat input
arc pressure
274A
334A
500A
500A
274A
334A
500A
500A
normalized pressure (p), normalized heat input (q)
normalized length (l)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5

Figure 26 Data

Table 4

s (ppm)	ρ (kg/m^3)	σ (N/m)	θ (degrees)	$α_e$ (degrees)	$ΔH_m$ (J/kg)	g (m/s^2)
230	6900	1.25	90	60	265000	9.81

		pi =	3.141593	= 180^o	
r_1 =	1	pi/2 =	1.570796	= 90^o	θ
r_2 =	0.4	pi/4 =	0.785398	= 45^o	θ/2

Table 5 **Results**

I (A)	V (mm/s)	L_a (mm)	H (mm)	D (mm)	P_{max} (kPa)	P_{max} (N/m^2)	$σ_P$ (mm)	Q_{max} (W/mm2)	$σ_Q$ (mm)	Q_{solid} (W/mm^2)	I_{eq}	q_{eq}	L_i
274	11.6	7.3	0.9	0.0917	1.4	1400	1.7	41	3.4	25.64	-	-	6.9
334	14.1	7.5	1.1	1.1250	1.8	1800	1.8	47	3.6	27.27	-	-	7.3
500	10.6	9.2	2.8	2.8333	3.0	3000	2.0	54	4.3	30.60	-	-	8.2
500	15.0	8.2	1.9	1.8750	3.0	3000	2.0	59	4.2	33.81	-	-	8.2
						2300							

Data for plotting of the pressure arc gaussian distribution.

l	p_a
0	1
0.1	0.980198673
0.2	0.923116346
0.3	0.835270211
0.4	0.726149037
0.5	0.60653066
0.6	0.486752256
0.7	0.375311099
0.8	0.2780373
0.9	0.197898699
1	0.135335283
1.1	0.088921617
1.2	0.056134763
1.3	0.034047455
1.4	0.019841095
1.5	0.011108997

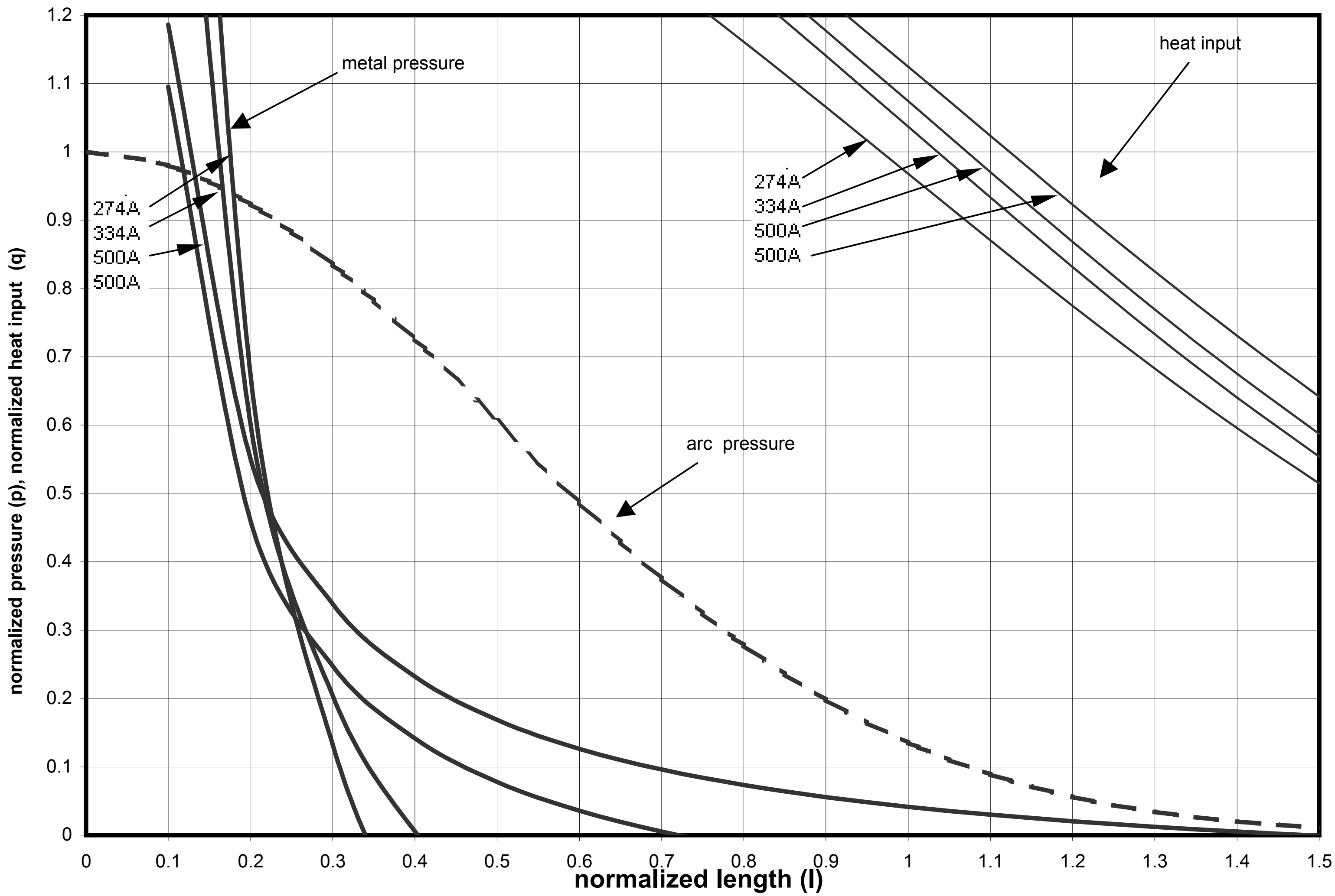
qa

1.604610298	1.712387769	1.76138	1.74142
1.59651961	1.703818791	1.753493	1.733025
1.572491492	1.678368281	1.730043	1.708083
1.533245561	1.636792761	1.691654	1.667307
1.479941308	1.580311503	1.639337	1.611851
1.414121201	1.510547129	1.574442	1.543251
1.337636587	1.42944823	1.498605	1.46336
1.252561357	1.339199121	1.413675	1.374258
1.161098982	1.24212257	1.321642	1.278169
1.065488689	1.140581501	1.22456	1.177364
0.96791631	1.036885418	1.124471	1.074078
0.870434582	0.933206561	1.023336	0.970428
0.774896734	0.831509802	0.922975	0.868348
0.682905938	0.733499016	0.825019	0.769532
0.595781909	0.640581321	0.730869	0.675402
0.514544689	0.553849259	0.641678	0.587085
274A	***334A***	***500A***	***500A .***

Calculation of the normalized pressure for each different case.

		Normalized length (l)														
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5
p_a	***274A***	2.294	0.673	0.132	-0.138	-0.300	-0.408	-0.485	-0.543	-0.588	-0.624	-0.654	-0.678	-0.699	-0.717	-0.732
	334A	1.792	0.601	0.204	0.006	-0.114	-0.193	-0.250	-0.292	-0.325	-0.352	-0.373	-0.391	-0.407	-0.420	-0.431
	500A	1.186	0.550	0.338	0.232	0.169	0.126	0.096	0.073	0.056	0.042	0.030	0.020	0.012	0.005	-0.001
	500A .	1.095	0.459	0.247	0.141	0.078	0.036	0.005	-0.017	-0.035	-0.049	-0.061	-0.070	-0.079	-0.086	-0.092

Figure 26



metal pressure
heat input
arc pressure
274A
334A
500A
500A
274A
334A
500A
500A
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
normalized pressure (p), normalized heat input (q)
normalized length (l)

Figure 27 Data

Inputs

s (ppm)	ρ (kg/m^3)	σ (N/m)	θ (degrees)	α_e (degrees)	ΔH_m (J/kg)	g (m/s^2)
400	7000	1.15	90	90	265000	0

		pi =	3.1415927	= 180°	
r_1 =	1	pi/2 =	1.5707963	= 90°	θ
r_2 =	0.4	pi/4 =	0.7853982	= 45°	θ/2

Inputs / **Results**

I (A)	V (mm/s)	L_a (mm)	H (mm)	D (mm)	P_{max} (kPa)	P_{max} (N/m^2)	σ_P (mm)	Q_{max} (W/mm2)	σ_Q (mm)	Q_{solid} (W/mm^2)	l_{eq}	q_{eq}	L_i
300	9.58	4.1	3.4	1.716	1.156	1156	1.883	68.55	2.913	40.341	1.041199554	0.41	7.5
350	8.39	4.4	3.9	1.958	1.401	1401	1.969	72.83	3.104	43.183	0.972815252	0.47	7.9
400	7.76	4.7	4.2	2.316	1.654	1654	2.046	76.47	3.284	45.380	0.986021358	0.47	8.2
450	6.36	5.2	5	2.775	1.915	1915	2.117	77.24	3.500	46.062	0.935221445	0.525	8.5
500	4.61	6.2	6.6	3.783	2.183	2183	2.182	72.98	3.808	43.611	0.859183789	0.63	8.7
						1661.528126							

Data for plotting of the pressure arc gaussian distribution.

l	p_a
0	1
0.1	0.980198673
0.2	0.923116346
0.3	0.835270211
0.4	0.726149037
0.5	0.60653066
0.6	0.486752256
0.7	0.375311099
0.8	0.2780373
0.9	0.197898699
1	0.135335283
1.1	0.088921617
1.2	0.056134763

qa

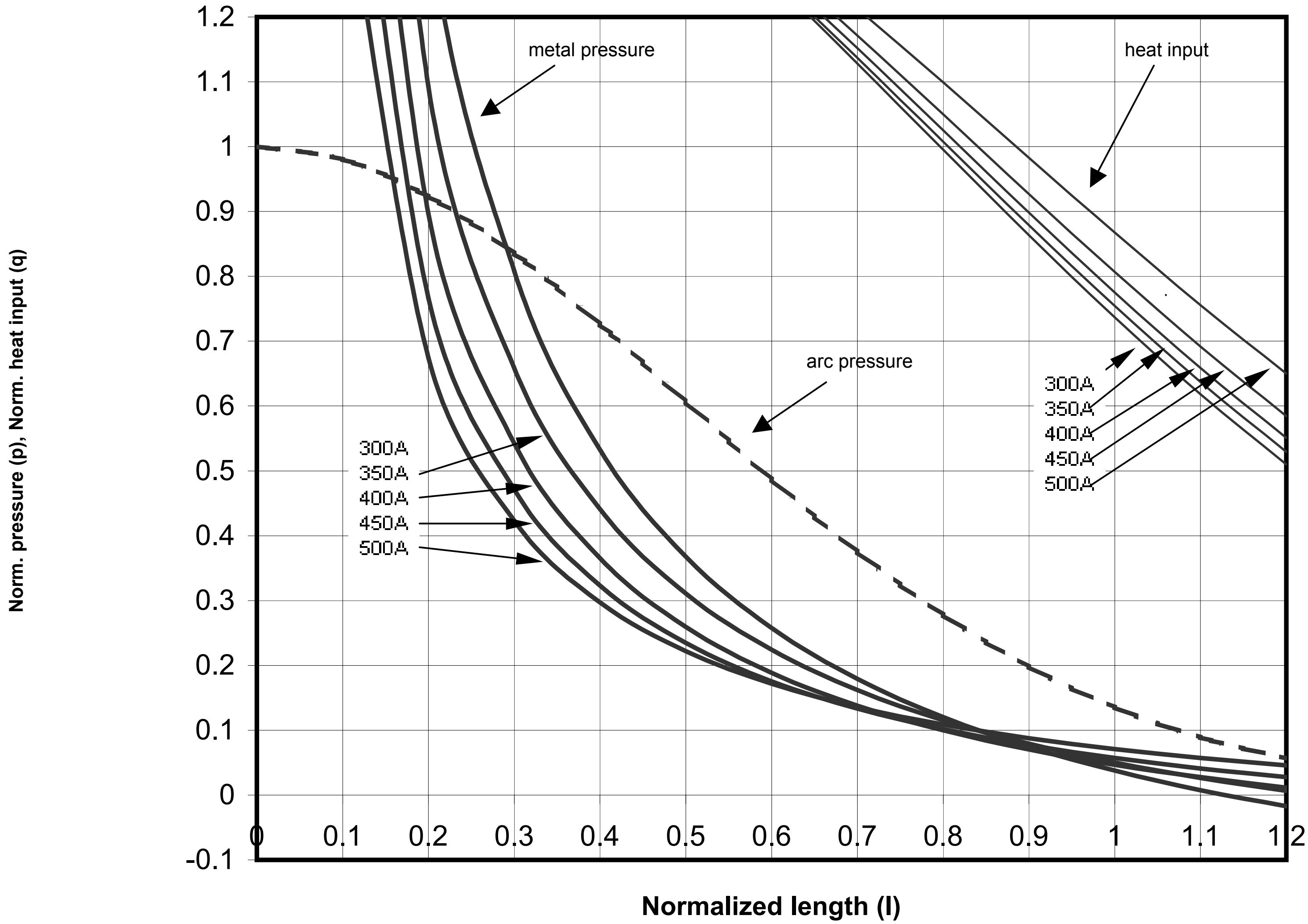
1.699308438	1.686480184	1.6850161	1.676788	1.673483
1.685167078	1.672963797	1.6719845	1.664563	1.662525
1.643445181	1.633061135	1.6334914	1.628418	1.630079
1.576191507	1.568660439	1.5712955	1.569912	1.577404
1.48663464	1.482743554	1.4881794	1.491519	1.506506
1.37892618	1.37915712	1.3877432	1.396452	1.420014
1.257822302	1.262327511	1.2741464	1.288448	1.321016
1.128337621	1.136948908	1.1518235	1.171526	1.212878
0.995406221	1.007674923	1.0252009	1.049737	1.099056
0.863581116	0.878841493	0.8984386	0.926943	0.982916
0.736796285	0.754242943	0.7752187	0.806621	0.867574
0.618206009	0.63697525	0.6585921	0.691719	0.755772
0.510106105	0.529351882	0.5508903	0.584566	0.649783
300A	***350A***	***400A***	***450A***	***500A***

		Normalized length (l)											
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2
p_a	300 A	3.009	1.358	0.808	0.533	0.368	0.258	0.179	0.120	0.074	0.038	0.008	-0.017
	350 A	2.396	1.093	0.658	0.441	0.311	0.224	0.162	0.115	0.079	0.050	0.026	0.007
	400 A	1.959	0.897	0.543	0.365	0.259	0.188	0.138	0.100	0.070	0.047	0.028	0.011
	450 A	1.653	0.767	0.471	0.323	0.235	0.175	0.133	0.102	0.077	0.057	0.041	0.028
	500 A	1.429	0.675	0.423	0.297	0.222	0.172	0.136	0.109	0.088	0.071	0.057	0.046

Use of solver to determine the values of l_{eq}.

Target, Solution	1.041199554	0.972815252	0.986021358	0.935221445	0.859183789
Eqn = 0	-0.090	-0.093	-0.093	-0.104	-0.133
	300 A	350 A	400 A	450 A	500 A

Figure 27



Norm. pressure (p), Norm. heat input (q)
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
metal pressure
heat input
arc pressure
300A
350A
400A
450A
500A
300A
350A
400A
450A
500A
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
Normalized length (l)

Figure 28 Data

Table 4

s (ppm)	ρ (kg/m³)	σ (N/m)	θ (degrees)	α_e (degrees)	ΔH_m (J/kg)	g (m/s²)
6	6900	1.82	30	60	265000	0

		pi =	3.141593	= 180°
r_1 =	1	pi/6 =	0.523599	= 30° θ
r_2 =	0.4	pi/12 =	0.261799	= 15° θ/2

Table 5 — Results

I (A)	V (mm/s)	L_a (mm)	H (mm)	D (mm)	P_{max} (kPa)	P_{max} (N/m²)	σ_P (mm)	Q_{max} (W/mm2)	σ_Q (mm)	Q_{solid} (W/mm²)	l_{eq}	q_{eq}	L_i
274	11.6	7.3	0.9	0.0917	1.4202	1400	1.721	41	3.4	25.64	1.41		6.9
334	14.1	7.5	1.1	1.1250	1.8169	1800	1.822	47	3.6	27.27	1.30	0.43	7.3
500	10.6	9.4	3.0	3.0000	3.0013	3000	2.048	53	4.4	29.88	1.04	0.62	8.2
500	15.0	8.5	2.2	2.1670	3.0013	3000	2.048	57	4.2	32.37	1.12	0.56	8.2
						2300							

Data for plotting of the pressure arc gaussian distribution.

l	p_a
0	1
0.1	0.980198673
0.2	0.923116346
0.3	0.835270211
0.4	0.726149037
0.5	0.60653066
0.6	0.486752256
0.7	0.375311099
0.8	0.2780373
0.9	0.197898699
1	0.135335283
1.1	0.088921617
1.2	0.056134763
1.3	0.034047455
1.4	0.019841095
1.5	0.011108997

qa

1.604610298	1.712388	1.774094	1.769594
1.59651961	1.703819	1.766259	1.761257
1.572491492	1.678368	1.74296	1.736483
1.533245561	1.636793	1.70481	1.695964
1.479941308	1.580312	1.652799	1.640822
1.414121201	1.510547	1.588252	1.57255
1.337636587	1.429448	1.512774	1.492953
1.252561357	1.339199	1.428185	1.404062
1.161098982	1.242123	1.336442	1.308052
1.065488689	1.140582	1.23957	1.207152
0.96791631	1.036885	1.139587	1.103564
0.870434582	0.933207	1.038435	0.999382
0.774896734	0.83151	0.937922	0.896528
0.682905938	0.733499	0.839672	0.7967
0.595781909	0.640581	0.745088	0.701333
0.514544689	0.553849	0.655332	0.611579
274A	***334A***	***500A***	***500A***

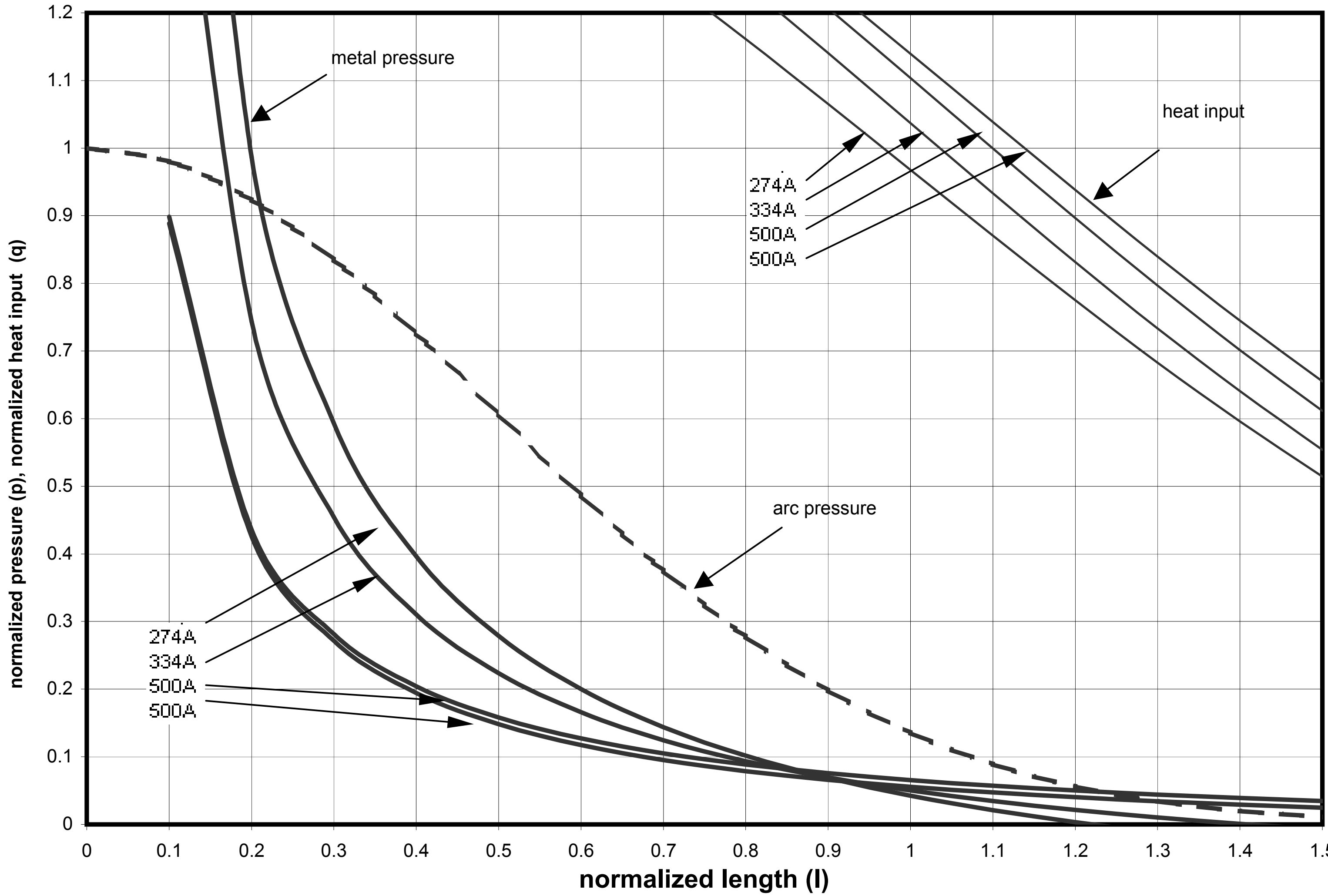
Calculation of the normalized pressure for each different case.

		Normalized length (l)														
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5
p_a	***274A***	2.167	0.987	0.593	0.397	0.279	0.200	0.144	0.102	0.069	0.043	0.021	0.003	-0.012	-0.025	-0.036
	334A	1.611	0.744	0.455	0.310	0.224	0.166	0.125	0.094	0.070	0.050	0.034	0.021	0.010	0.001	-0.008
	500A	0.899	0.436	0.282	0.204	0.158	0.127	0.105	0.089	0.076	0.065	0.057	0.050	0.044	0.039	0.035
	500A .	0.889	0.426	0.272	0.195	0.148	0.117	0.095	0.079	0.066	0.056	0.047	0.040	0.034	0.029	0.025

Use of solver to determine the values of l_{eq}.

Target, Solution	1.416470415	1.301441233	1.044502189	1.117053533
Eqn = 0	-0.045	-0.024	-0.051	-0.037
	274A	***334A***	***500A***	***500A .***

Figure 28



metal pressure
heat input
arc pressure
274A
334A
500A
500A
274A
334A
500A
500A
normalized pressure (p), normalized heat input (q)
normalized length (l)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5

Figure 29 Data

Table 4

s (ppm)	ρ (kg/m^3)	σ (N/m)	θ (degrees)	$α_e$ (degrees)	$ΔH_m$ (J/kg)	g (m/s^2)
230	6900	1.25	90	60	265000	0

		pi =	3.141593	= 180°	
r_1 =	1	pi/2 =	1.570796	= 90°	θ
r_2 =	0.4	pi/4 =	0.785398	= 45°	θ/2

Table 5 **Results**

I (A)	V (mm/s)	L_a (mm)	H (mm)	D (mm)	P_{max} (kPa)	P_{max} (N/m^2)	$σ_P$ (mm)	Q_{max} (W/mm2)	$σ_Q$ (mm)	Q_{solid} (W/mm^2)	l_{eq}	q_{eq}	L_i
274	11.6	7.3	0.9	0.0917	1.4	1400	1.7	41	3.4	25.64	-	-	6.9
334	14.1	7.5	1.1	1.1250	1.8	1800	1.8	47	3.6	27.27	-	-	7.3
500	10.6	9.2	2.8	2.8333	3.0	3000	2.0	54	4.3	30.60	-	-	8.2
500	15.0	8.2	1.9	1.8750	3.0	3000	2.0	59	4.2	33.81	-	-	8.2
						2300							

Data for plotting of the pressure arc gaussian distribution.

l	p_a
0	1
0.1	0.980198673
0.2	0.923116346
0.3	0.835270211
0.4	0.726149037
0.5	0.60653066
0.6	0.486752256
0.7	0.375311099
0.8	0.2780373
0.9	0.197898699
1	0.135335283
1.1	0.088921617
1.2	0.056134763
1.3	0.034047455
1.4	0.019841095
1.5	0.011108997

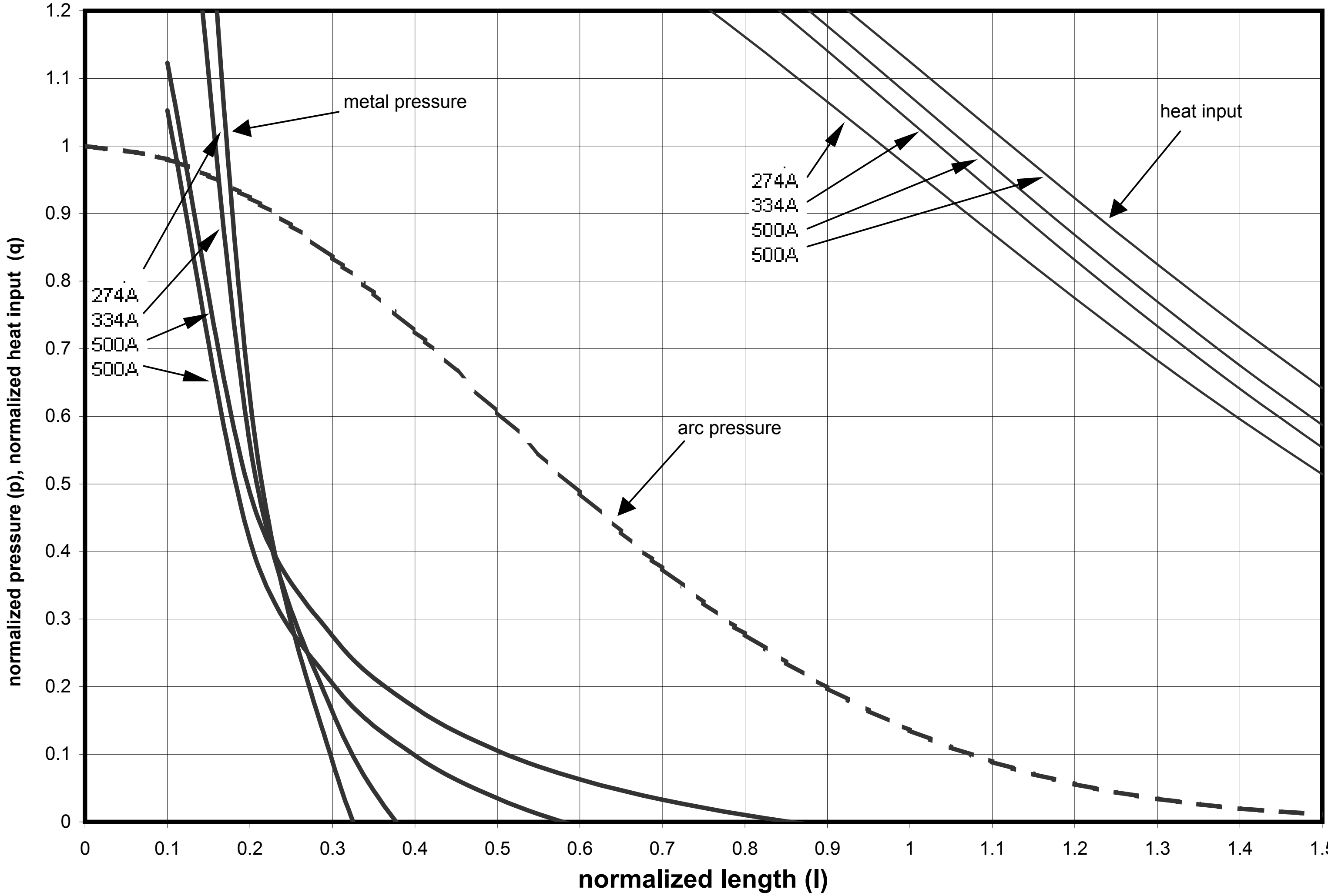
qa

1.604610298	1.712387769	1.76138	1.74142
1.59651961	1.703818791	1.753493	1.733025
1.572491492	1.678368281	1.730043	1.708083
1.533245561	1.636792761	1.691654	1.667307
1.479941308	1.580311503	1.639337	1.611851
1.414121201	1.510547129	1.574442	1.543251
1.337636587	1.42944823	1.498605	1.46336
1.252561357	1.339199121	1.413675	1.374258
1.161098982	1.24212257	1.321642	1.278169
1.065488689	1.140581501	1.22456	1.177364
0.96791631	1.036885418	1.124471	1.074078
0.870434582	0.933206561	1.023336	0.970428
0.774896734	0.831509802	0.922975	0.868348
0.682905938	0.733499016	0.825019	0.769532
0.595781909	0.640581321	0.730869	0.675402
0.514544689	0.553849259	0.641678	0.587085
274A	***334A***	***500A***	***500A .***

Calculation of the normalized pressure for each different case.

		Normalized length (l)														
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5
p_a	***274A***	2.251	0.629	0.089	-0.181	-0.344	-0.452	-0.529	-0.587	-0.632	-0.668	-0.697	-0.722	-0.743	-0.760	-0.776
	334A	1.750	0.560	0.163	-0.036	-0.155	-0.234	-0.291	-0.334	-0.367	-0.393	-0.415	-0.433	-0.448	-0.461	-0.473
	500A	1.123	0.487	0.275	0.169	0.106	0.063	0.033	0.010	-0.008	-0.022	-0.033	-0.043	-0.051	-0.058	-0.064
	500A .	1.052	0.417	0.205	0.099	0.035	-0.007	-0.038	-0.060	-0.078	-0.092	-0.104	-0.113	-0.121	-0.128	-0.135

Figure 29



metal pressure
heat input
274A
334A
500A
500A
274A
334A
500A
500A
arc pressure
normalized pressure (p), normalized heat input (q)
normalized length (l)

Summary for g=9.81 m/s^2

Table 3

	S (ppm)	I (A)	V (mm/s)	La (mm)	H (mm)	D (mm)	leq	qeq
	400	300	9.58	4.10	3.40	1.72	0.68	1.16
	400	350	8.39	4.40	3.90	1.96	0.75	1.07
	400	400	7.76	4.70	4.20	2.32	0.81	1.01
	400	450	6.36	5.20	5.00	2.78	0.80	1.05
	400	500	4.61	6.20	6.60	3.78	0.74	1.17
Mean	400	400	7.34	4.92	4.62	2.51	0.76	1.09

l	p_a	*qa* 300A	350A	400A	450A	500A	Mean
0	1	1.699308	1.68648	1.685016	1.676788	1.673483	1.684215
0.1	0.980199	1.685167	1.672964	1.671985	1.664563	1.662525	1.671441
0.2	0.923116	1.643445	1.633061	1.633491	1.628418	1.630079	1.633699
0.3	0.83527	1.576192	1.56866	1.571296	1.569912	1.577404	1.572693
0.4	0.726149	1.486635	1.482744	1.488179	1.491519	1.506506	1.491117
0.5	0.606531	1.378926	1.379157	1.387743	1.396452	1.420014	1.392459
0.6	0.486752	1.257822	1.262328	1.274146	1.288448	1.321016	1.280752
0.7	0.375311	1.128338	1.136949	1.151824	1.171526	1.212878	1.160303
0.8	0.278037	0.995406	1.007675	1.025201	1.049737	1.099056	1.035415
0.9	0.197899	0.863581	0.878841	0.898439	0.926943	0.982916	0.910144
1	0.135335	0.736796	0.754243	0.775219	0.806621	0.867574	0.788091
1.1	0.088922	0.618206	0.636975	0.658592	0.691719	0.755772	0.672253
1.2	0.056135	0.510106	0.529352	0.55089	0.584566	0.649783	0.564939

		Normalized length (l)											
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2
p_a	300 A	3.211	1.560	1.010	0.735	0.570	0.460	0.381	0.322	0.276	0.240	0.210	0.185
	350 A	2.588	1.284	0.850	0.632	0.502	0.415	0.353	0.307	0.270	0.241	0.218	0.198
	400 A	2.133	1.071	0.717	0.540	0.434	0.363	0.312	0.274	0.245	0.221	0.202	0.186
	450 A	1.833	0.946	0.650	0.503	0.414	0.355	0.313	0.281	0.256	0.237	0.220	0.207
	500 A	1.637	0.882	0.631	0.505	0.430	0.379	0.343	0.316	0.295	0.279	0.265	0.254
	Mean	2.280245	1.148715	0.771538	0.582949	0.469796	0.394361	0.340478	0.300067	0.268635	0.24349	0.222917	0.205772

Table 5a

	S (ppm)	I (A)	V (mm/s)	La (mm)	H (mm)	D (mm)	leq	qeq
	6	274	11.60	7.30	0.90	0.09	1.06	1.12
	6	334	14.10	7.50	1.10	1.13	1.13	0.99
	6	500	10.60	9.40	3.00	3.00	1.20	0.88
	6	500	15.00	8.50	2.20	2.17	1.29	0.78
Mean	6	402	12.83	8.18	1.80	1.60	1.17	0.94

l	p_a	*qa*				Mean
0	1	1.60461	1.712388	1.774094	1.769594	1.715171
0.1	0.980199	1.59652	1.703819	1.766259	1.761257	1.706964
0.2	0.923116	1.572491	1.678368	1.74296	1.736483	1.682576
0.3	0.83527	1.533246	1.636793	1.70481	1.695964	1.642703
0.4	0.726149	1.479941	1.580312	1.652799	1.640822	1.588468
0.5	0.606531	1.414121	1.510547	1.588252	1.57255	1.521368
0.6	0.486752	1.337637	1.429448	1.512774	1.492953	1.443203
0.7	0.375311	1.252561	1.339199	1.428185	1.404062	1.356002
0.8	0.278037	1.161099	1.242123	1.336442	1.308052	1.261929
0.9	0.197899	1.065489	1.140582	1.23957	1.207152	1.163198
1	0.135335	0.967916	1.036885	1.139587	1.103564	1.061988
1.1	0.088922	0.870435	0.933207	1.038435	0.999382	0.960365
1.2	0.056135	0.774897	0.83151	0.937922	0.896528	0.860214

		Normalized length (l)											
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2
p_a	274 A	2.211	1.030	0.637	0.440	0.322	0.243	0.187	0.145	0.112	0.086	0.065	0.047
	334 A	1.652	0.785	0.496	0.352	0.265	0.207	0.166	0.135	0.111	0.092	0.076	0.063
	500 A	0.966	0.503	0.349	0.272	0.226	0.195	0.173	0.156	0.143	0.133	0.125	0.118
	500 A	0.938	0.476	0.321	0.244	0.198	0.167	0.145	0.128	0.116	0.105	0.097	0.090
	Mean	1.153565	0.558933	0.360722	0.261617	0.202154	0.162511	0.134196	0.112959	0.096441	0.083227	0.072416	0.063406

Table 5b

	S (ppm)	I (A)	V (mm/s)	La (mm)	H (mm)	D (mm)	leq	qeq
	230	274	11.60	7.30	0.90	0.09		
	230	334	14.10	7.50	1.10	1.13		
	230	500	10.60	9.20	2.80	2.83		
	230	500	15.00	8.20	1.90	1.88		
Mean	230	402	12.83	8.05	1.68	1.48	0.00	0.00

l	p_a	*qa*				Mean
0	1	1.60461	1.712388	1.76138	1.74142	1.70495
0.1	0.980199	1.59652	1.703819	1.753493	1.733025	1.696714
0.2	0.923116	1.572491	1.678368	1.730043	1.708083	1.672246
0.3	0.83527	1.533246	1.636793	1.691654	1.667307	1.63225
0.4	0.726149	1.479941	1.580312	1.639337	1.611851	1.57786
0.5	0.606531	1.414121	1.510547	1.574442	1.543251	1.51059
0.6	0.486752	1.337637	1.429448	1.498605	1.46336	1.432262
0.7	0.375311	1.252561	1.339199	1.413675	1.374258	1.344923
0.8	0.278037	1.161099	1.242123	1.321642	1.278169	1.250758
0.9	0.197899	1.065489	1.140582	1.22456	1.177364	1.151998
1	0.135335	0.967916	1.036885	1.124471	1.074078	1.050838
1.1	0.088922	0.870435	0.933207	1.023336	0.970428	0.949351
1.2	0.056135	0.774897	0.83151	0.922975	0.868348	0.849432

		Normalized length (l)											
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2
p_a	274 A	2.294	0.673	0.132	-0.138	-0.300	-0.408	-0.485	-0.543	-0.588	-0.624	-0.654	-0.678
	334 A	1.792	0.601	0.204	0.006	-0.114	-0.193	-0.250	-0.292	-0.325	-0.352	-0.373	-0.391
	500 A	1.186	0.550	0.338	0.232	0.169	0.126	0.096	0.073	0.056	0.042	0.030	0.020
	500 A	1.095	0.459	0.247	0.141	0.078	0.036	0.005	-0.017	-0.035	-0.049	-0.061	-0.070
	Mean	1.273493	0.456691	0.184423	0.04829	-0.03339	-0.08784	-0.12674	-0.15591	-0.1786	-0.19675	-0.2116	-0.22398

Summary for g=0

Table 3

	S (ppm)	I (A)	V (mm/s)	La (mm)	H (mm)	leq	qeq
	400	300	9.58	4.1	3.4	0.68	1.16
	400	350	8.39	4.4	3.9	0.75	1.07
	400	400	7.76	4.7	4.2	0.81	1.01
	400	450	6.36	5.2	5	0.80	1.05
	400	500	4.61	6.2	6.6	0.74	1.17
Mean	400	400	7.34	4.92	4.62	0.756	1.092

l	p_a	*qa*					Mean
0	1	1.699308	1.68648	1.685016	1.676788	1.673483	1.684215
0.1	0.980199	1.685167	1.672964	1.671985	1.664563	1.662525	1.671441
0.2	0.923116	1.643445	1.633061	1.633491	1.628418	1.630079	1.633699
0.3	0.83527	1.576192	1.56866	1.571296	1.569912	1.577404	1.572693
0.4	0.726149	1.486635	1.482744	1.488179	1.491519	1.506506	1.491117
0.5	0.606531	1.378926	1.379157	1.387743	1.396452	1.420014	1.392459
0.6	0.486752	1.257822	1.262328	1.274146	1.288448	1.321016	1.280752
0.7	0.375311	1.128338	1.136949	1.151824	1.171526	1.212878	1.160303
0.8	0.278037	0.995406	1.007675	1.025201	1.049737	1.099056	1.035415
0.9	0.197899	0.863581	0.878841	0.898439	0.926943	0.982916	0.910144
1	0.135335	0.736796	0.754243	0.775219	0.806621	0.867574	0.788091
1.1	0.088922	0.618206	0.636975	0.658592	0.691719	0.755772	0.672253
1.2	0.056135	0.510106	0.529352	0.55089	0.584566	0.649783	0.564939
		300A	***350A***	***400A***	***450A***	***500A***	

		Normalized length (l)											
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2
p_a	300 A	3.009	1.358	0.808	0.533	0.368	0.258	0.179	0.120	0.074	0.038	0.008	-0.017
	350 A	2.396	1.093	0.658	0.441	0.311	0.224	0.162	0.115	0.079	0.050	0.026	0.007
	400 A	1.959	0.897	0.543	0.365	0.259	0.188	0.138	0.100	0.070	0.047	0.028	0.011
	450 A	1.653	0.767	0.471	0.323	0.235	0.175	0.133	0.102	0.077	0.057	0.041	0.028
	500 A	1.429	0.675	0.423	0.297	0.222	0.172	0.136	0.109	0.088	0.071	0.057	0.046
	Mean	2.089335	0.957805	0.580628	0.392039	0.278886	0.203451	0.149568	0.109157	0.077725	0.05258	0.032007	0.014862

Table 5a

	S (ppm)	I (A)	V (mm/s)	La (mm)	H (mm)	leq	qeq
	6	274	11.6	7.3	0.9	1.06	1.12
	6	334	14.1	7.5	1.1	1.13	0.99
	6	500	10.6	9.4	3	1.2	0.88
	6	500	15	8.5	2.2	1.29	0.78
Mean	6	402	12.825	8.175	1.8	1.17	0.9425

l	p_a	*qa*				Mean
0	1	1.60461	1.712388	1.774094	1.769594	1.715171
0.1	0.980199	1.59652	1.703819	1.766259	1.761257	1.706964
0.2	0.923116	1.572491	1.678368	1.74296	1.736483	1.682576
0.3	0.83527	1.533246	1.636793	1.70481	1.695964	1.642703
0.4	0.726149	1.479941	1.580312	1.652799	1.640822	1.588468
0.5	0.606531	1.414121	1.510547	1.588252	1.57255	1.521368
0.6	0.486752	1.337637	1.429448	1.512774	1.492953	1.443203
0.7	0.375311	1.252561	1.339199	1.428185	1.404062	1.356002
0.8	0.278037	1.161099	1.242123	1.336442	1.308052	1.261929
0.9	0.197899	1.065489	1.140582	1.23957	1.207152	1.163198
1	0.135335	0.967916	1.036885	1.139587	1.103564	1.061988
1.1	0.088922	0.870435	0.933207	1.038435	0.999382	0.960365
1.2	0.056135	0.774897	0.83151	0.937922	0.896528	0.860214

		Normalized length (l)											
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2
p_a	274 A	2.167	0.987	0.593	0.397	0.279	0.200	0.144	0.102	0.069	0.043	0.021	0.003
	334 A	1.611	0.744	0.455	0.310	0.224	0.166	0.125	0.094	0.070	0.050	0.034	0.021
	500 A	0.899	0.436	0.282	0.204	0.158	0.127	0.105	0.089	0.076	0.065	0.057	0.050
	500 A	0.889	0.426	0.272	0.195	0.148	0.117	0.095	0.079	0.066	0.056	0.047	0.040
	Mean	1.113124	0.518491	0.320281	0.221175	0.161712	0.12207	0.093754	0.072517	0.056	0.042786	0.031974	0.022964

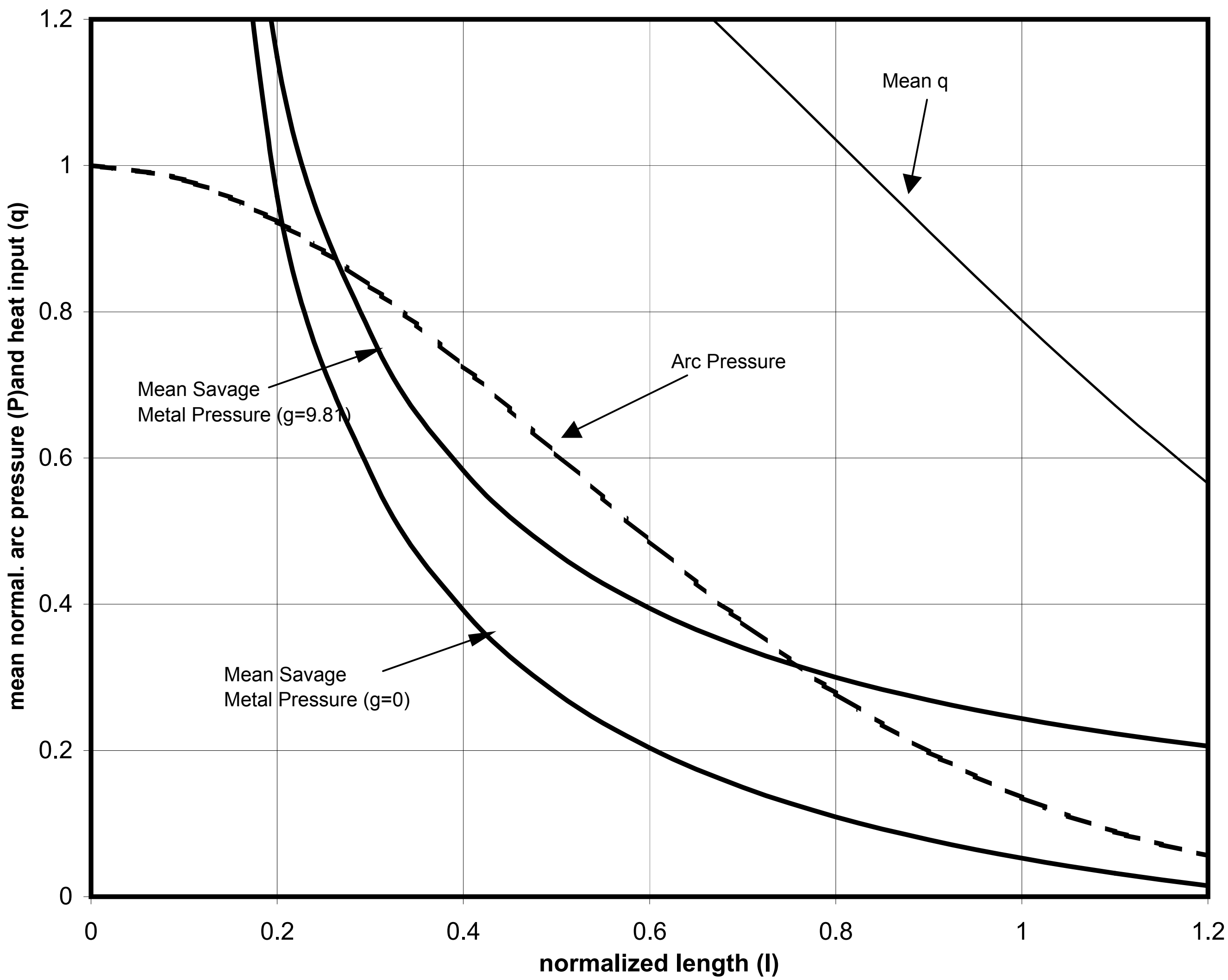
Table 5b

	S (ppm)	I (A)	V (mm/s)	La (mm)	H (mm)	leq	qeq
	230	274	11.6	7.3	0.9		
	230	334	14.1	7.5	1.1		
	230	500	10.6	9.2	2.8		
	230	500	15	8.2	1.9		
Mean	230	402	12.825	8.05	1.675	0	0

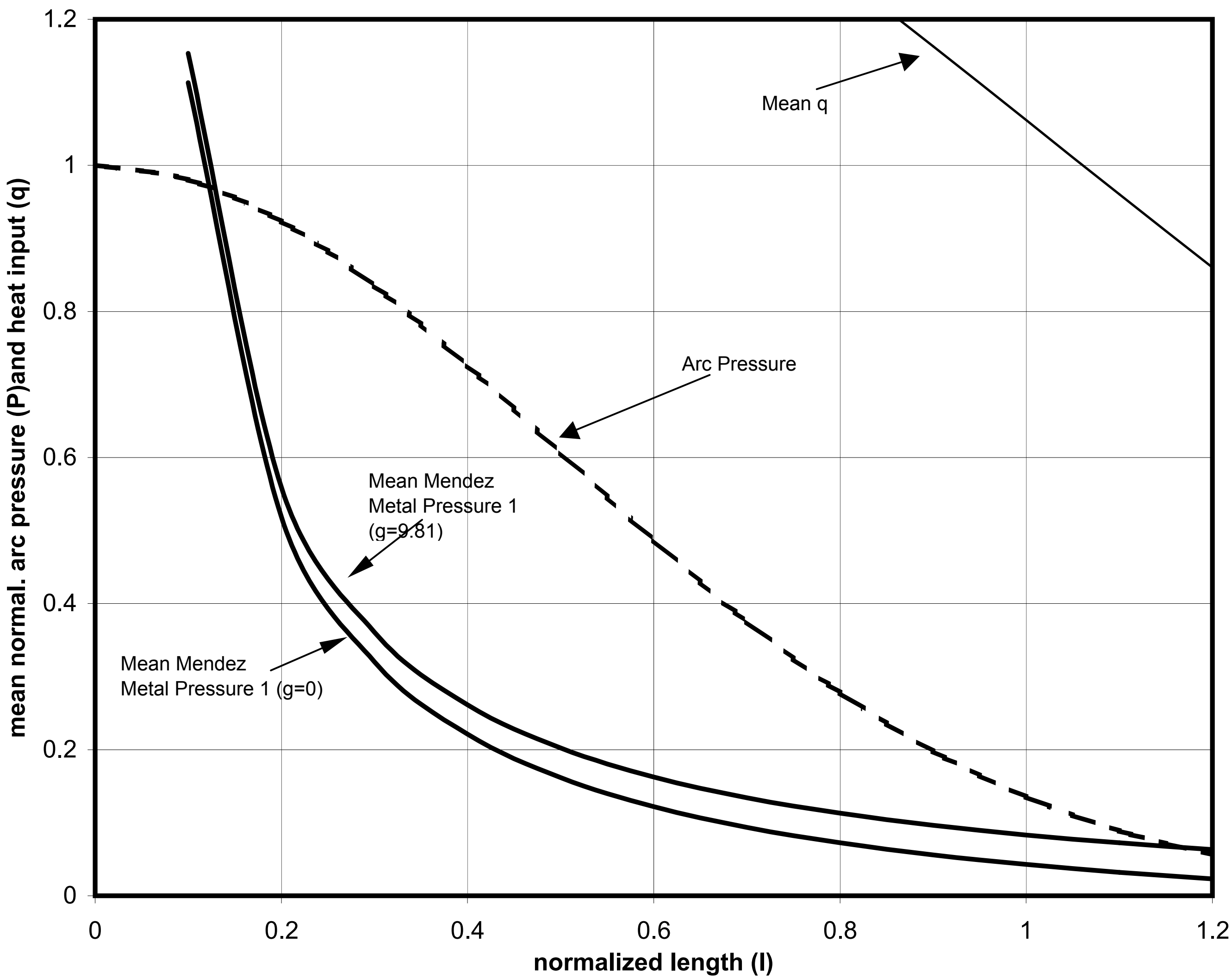
l	p_a	*qa*				Mean
0	1	1.60461	1.712388	1.76138	1.74142	1.70495
0.1	0.980199	1.59652	1.703819	1.753493	1.733025	1.696714
0.2	0.923116	1.572491	1.678368	1.730043	1.708083	1.672246
0.3	0.83527	1.533246	1.636793	1.691654	1.667307	1.63225
0.4	0.726149	1.479941	1.580312	1.639337	1.611851	1.57786
0.5	0.606531	1.414121	1.510547	1.574442	1.543251	1.51059
0.6	0.486752	1.337637	1.429448	1.498605	1.46336	1.432262
0.7	0.375311	1.252561	1.339199	1.413675	1.374258	1.344923
0.8	0.278037	1.161099	1.242123	1.321642	1.278169	1.250758
0.9	0.197899	1.065489	1.140582	1.22456	1.177364	1.151998
1	0.135335	0.967916	1.036885	1.124471	1.074078	1.050838
1.1	0.088922	0.870435	0.933207	1.023336	0.970428	0.949351
1.2	0.056135	0.774897	0.83151	0.922975	0.868348	0.849432

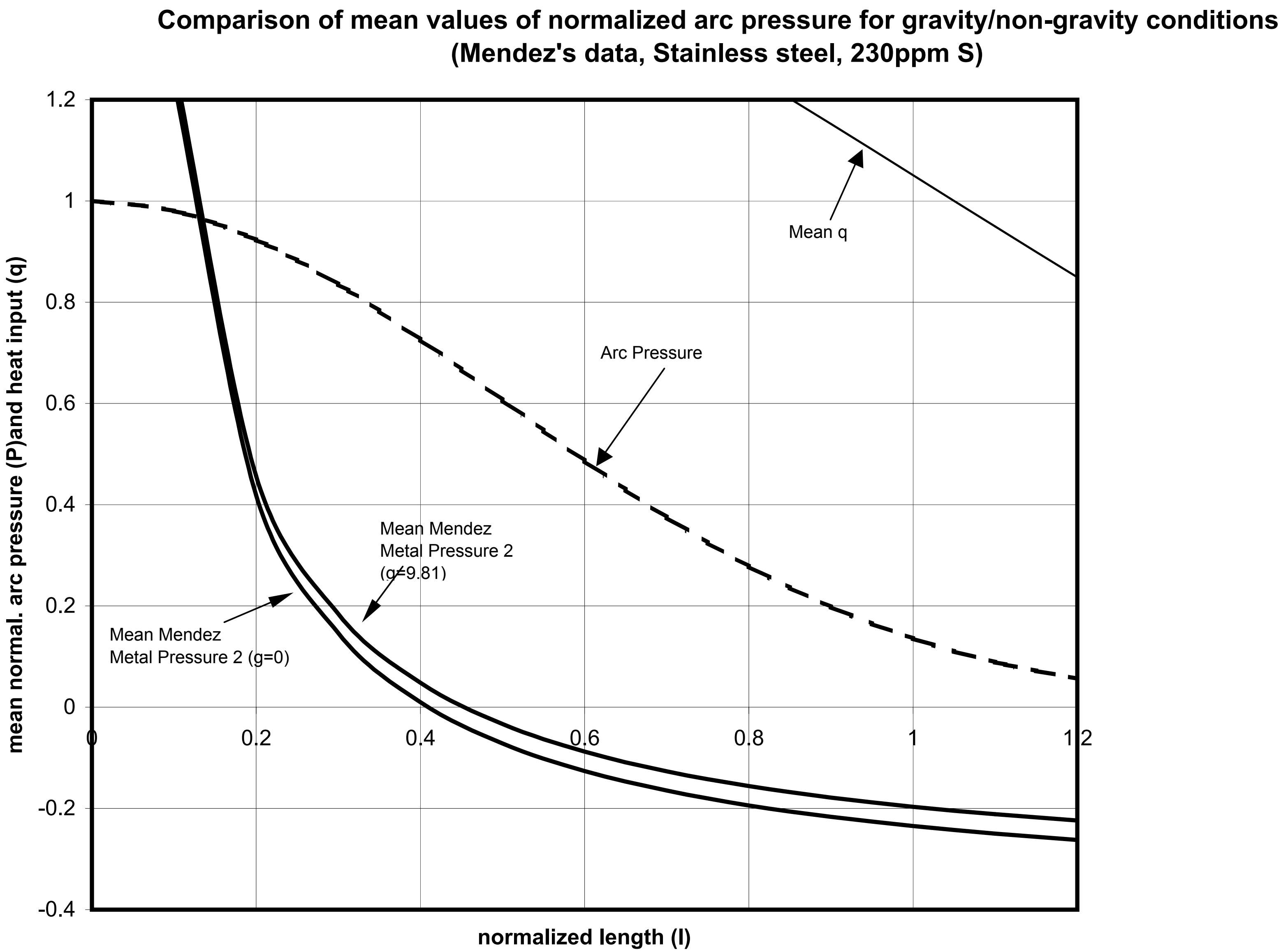
		Normalized length (l)											
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2
p_a	274 A	2.251	0.629	0.089	-0.181	-0.344	-0.452	-0.529	-0.587	-0.632	-0.668	-0.697	-0.722
	334 A	1.750	0.560	0.163	-0.036	-0.155	-0.234	-0.291	-0.334	-0.367	-0.393	-0.415	-0.433
	500 A	1.123	0.487	0.275	0.169	0.106	0.063	0.033	0.010	-0.008	-0.022	-0.033	-0.043
	500 A	1.052	0.417	0.205	0.099	0.035	-0.007	-0.038	-0.060	-0.078	-0.092	-0.104	-0.113
	Mean	1.235308	0.418506	0.146238	0.010104	-0.07158	-0.12603	-0.16492	-0.1941	-0.21679	-0.23494	-0.24979	-0.26216

Comparison of mean values of normalized arc pressure for gravity/non-gravity conditions (Savage's data)



Comparison of mean values of normalized arc pressure for gravity/non-gravity conditions (Mendez's data, Stainless steel, 6ppm S)





Comparison of mean values of normalized arc pressure for gravity/non-gravity conditions
(Mendez's data, Stainless steel, 230ppm S)
mean normal. arc pressure (P)and heat input (q)
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
0
0.2
0.4
0.6
0.8
1
1.2
Mean q
Arc Pressure
Mean Mendez
Metal Pressure 2
(g=9.81)
Mean Mendez
Metal Pressure 2 (g=0)
normalized length (l)

	Savage		Mendez 1		Mendez 2	
	g=9.81	g=0	g=9.81	g=0	g=9.81	g=0
1st Term	0.201943	0	0.043514	0	0.043514	0
2nd Term	-0.292551	-0.292551	-0.193519	-0.193519	-0.992063	-0.992063
3rd Term	3.301956	3.301956	2.360769	2.360769	3.242815	3.242815

All these values for the 3rd term are for l=0.1, for greater values of l (0.2…1.2),the 3rd term decreases significantly

Final Result

		0.1	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1**	**1.1**	**1.2**
Savage	**I=300A**	3.211348	1.56037	1.01004	0.734881	0.569783	0.4597	0.3811	0.322136	0.276276	0.239587	0.20957	0.184555
Patricio 1	**I=274A**	2.210765	1.03038	0.63692	0.440188	0.322149	0.2435	0.187248	0.145092	0.112303	0.086072	0.064611	0.046726
Patricio 2	**I=274A**	2.294265	0.672858	0.13239	-0.137845	-0.299986	-0.4081	-0.48529	-0.543197	-0.588236	-0.624268	-0.653748	-0.678315

3rd Term Only

Savage	**I=300A**	3.301956	1.650978	1.10065	0.825489	0.660391	0.5503	0.471708	0.412745	0.366884	0.330196	0.300178	0.275163
Patricio 1	**I=274A**	2.360769	1.180385	0.78692	0.590192	0.472154	0.3935	0.337253	0.295096	0.262308	0.236077	0.214615	0.196731
Patricio 2	**I=274A**	3.242815	1.621407	1.08094	0.810704	0.648563	0.5405	0.463259	0.405352	0.360313	0.324281	0.294801	0.270235

<u>Conclusions:</u>

1) The effect that H has on the normalized arc pressure increases with the increase of the normalized length.
2) Also the effect of H is much bigger on the first term of the equation (normalized hydrostatic pressure).
3) In the case of Savage's experimental data, the depth of the penetration (D), as well as the height of the metal column (H), are considerably greater than the results taken from both Mendez's experiements. Savage's welds are deeper by a factor of 3.
4) Taking 3 and 4 into account, when we set gravity equal to zero (g=0), the normalized hydrostatic pressure becomes zero. Consequently, the experiment that had the greater penetration is going to have the bigger change in the normalized arc pressure, since the "balance" that the hydrostatic term was providing is gone.